DOE/MC/21181-1950, Vol. 6
(DE86006636)

Geological Evolution and Analysis of Confirmed or Suspected Gas Hydrate Localities

Volume 6. Basin Analysis, Formation and Stability of Gas Hydrates in the Panama Basin

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Work Performed Under Contract No.: DE-AC21-84MC-21181

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March 1986

PREFACE

This document is Volume VI of a series of reports entitled "Geological Evolution and Analysis of Confirmed or Suspected Gas Hydrate Localities." Volume VI is titled, "Basin Analysis, Formation and Stability of Gas Hydrates in the Panama Basin." This report presents a geological description of the Panama Basin, including regional and local structural settings, geomorphology, geological history, stratigraphy, and physical properties. It provides the necessary regional and geological background for more in-depth research of the area. Detailed discussion of bottom simulating acoustic reflectors, sediment acoustic properties, distribution of hydrates within the sediments, and the relation of hydrate distribution to other features such as salt diapirism are also included. The formation and stabilization of gas hydrates in sediments are considered in terms of phase relations, nucleation, and crystallization constraints, gas solubility, pore fluid chemistry, inorganic diagenesis, and sediment organic content. Together with a depositional analysis of the area, this report is a better understanding of the thermal evolution of the locality. It should lead to an assessment of the potential for both biogenic and thermogenic hydrocarbon generation.

Project Manager
Gas Hydrates

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EXECUTIVE SUMMARY

This is one of a series of reports prepared by Geoexplorers International, Inc. at the request of the U.S. Department of Energy (DOE) - Morgantown Energy Technology Center (METC).

Selection of the Panama Basin for gas hydrate study was based on earlier information by Shipley et al. (1979) who reported that multichannel seismic surveys revealed the presence of bottom simulating reflectors (BSRs). The BSRs are being considered as indirect, but very reliable evidence for the base of the gas hydrate-bearing zone (Shipley et al., 1979; Dillon and Paull, 1983).

In the Panama Basin, geophysical surveys were conducted in the 1960s and early 1970s. Most of the surveys did not include multichannel seismic techniques, and in spite of a relatively dense coverage by the seismic profiles, there are large data gaps. Therefore, and because there are only a few widely dispersed Deep Sea Drilling Project (DSDP) sites in the Panama Basin, it was necessary for this study to cover an extremely large region (approximately 1,200,000 km^2).

The scope of this study is to relate the geological environments to gas hydrate formation and stability, and to assess the gas resources potential in the Panama Basin. The results of this study and the most up-to-date information pertaining to the study objectives can be summarized as follows (see also Table 1):

1. The Panama Basin is naturally bounded. To the south is the Carnegie Ridge; the Cocos Ridge forms the western and northwestern boundary of the basin; the continental shelf and the land territories of Panama, Colombia, and Ecuador limit the Panama Basin to the north and east respectively.

2. Bathymetry of the Panama Basin is well defined (see Figures 1 and 2).

3. The depth of the basin ranges from some ten meters at the continental shelf (40 to 80 km wide) and around the islands, up to 3,600 m below sea level in the central parts of the basin. The oceanic depth of the basin floor in the Yaquina Graben exceeds 5,000 m (see Figure 2).

4. Geomorphology of the basin is mostly very rugged and generally it is controlled by major faulting systems, along the ridges, and by volcanogenic activity, particularly within the Galapagos and Cocos Islands.

5. In the Panama Basin along the major ridges are tectono-sedimentary terraces up to 100 km long and 20 km wide.

6. The structural development of the Panama Basin resulted from a complex interplay of four major tectonic plates: Nazca, Cocos, South American, and Caribbean. Thus, the internal structure of the Panama Basin is very complex. Besides prevailing ridge type structures, there are also systems of grabens and troughs, e.g. Yaquina Graben and Eastern Panama Basin.

7. The most coherent and widely accepted hypothesis on the structural evolution of the Panama Basin which ties all the structural elements together was presented by van Andel et al. (1971).

8. Seismic data reveals horizontal stratification of sediments unevenly covering the ridges.

9. The sedimentary pattern in the Panama Basin is defined by its tectonic history and high biogenic production. The central part of the Galapagos Rifting Zone and highly elevated ridges and other tectonic blocks are free of sediments. Contrarily, the thickest sedimentary sequence (up to 1,500 m) occurs in the marginal troughs of the basin.

10. The deep oceanic sedimentary sequence is commonly incomplete due to erosional effects of bottom currents, slumping along steep slopes, and volcanic activity.

11. Presently available data are insufficient for detailed lithostratigraphic correlation of the sedimentary sequence in the Panama Basin. Nevertheless, lithological features have been used for lithostratigraphic subdivision of the sedimentary sequence of each individual DSDP site. A brief lithological description of each unit with emphasis on the organic matter content in each DSDP site is also included in this report.

    The oldest stratigraphic sequence of the sedimentary cover in the Panama Basin appears to be of middle Miocene age. The upper sections of the sedimentary sequence usually consist of nannofossil chalk oozes. Siliceous cherts and pyrite-bearing clays are also common.

12. The rates of sedimentation show significant differences resulting from the combination of biogenic matter production, bathymetry, and intensity of upwelling oceanic currents.

13. Generally, in the Panama Basin, there are high heat flow values (up to 200 mW/m^2 according to Bowin (1976). However, the heat flow pattern is not conformable with structural features of the basin.

14. In the process of thorough analysis of seismic data, the bottom simulating reflectors (BSRs) originally reported from Panama Basin by Shipley et al. (1979) have been confirmed and one new location with BSRs, along Panama, the Colombia and Ecuador continental margins was found.

15. The identified BSRs represent only a fraction of possibly existing anomalous seismic reflectors related to gas hydrates.

16. It is concluded that the most favorable conditions for gas hydrates occur in areas of relatively flat continental slopes and upper rises where the oceanic water depth does not exceed 2,000 m.

17. In the vertical section, the top of the sedimentary sequence in the continental margins of the Panama Basin appears to be very favorable for the disseminated type of gas hydrates. Yet, much better conditions for gas hydrate formation and stability exist in the sediments of high permeability.

18. Isotopic and geochemical data are needed for more accurate determination of the hydrocarbon origin and more satisfactory assessment of gas resource potential.

19. Because of insufficient data, the assessment of gas resource potential in the Panama Basin is being made only hypothetically. Nevertheless, we are quite confident that the thickness of the gas hydrate stability zone varies from 200 to 336 m (based on the presence of BSRs and thermal-pressure conditions). The maximum ocean depth at the locations with BSRs is approximately 2,600 m.

20. Thus, estimated resources of hydrocarbon gas accumulated in the hypothetical hydrate zone of the continental margin within the Panama Basin, amounts to 6.8 TCF per 1 m of thickness of sediment saturated with gas hydrates. In a possible 300 m thickness of gas hydrate-bearing zone, potential gas resources are estimated at 2,040 TCF.

TABLE 1, Summary Data of Basin Analysis, Formation and Stability of Gas Hydrates in the Panama Basin, is located in the pocket at the end of the report.

INTRODUCTION

The study of environments favorable for gas hydrates in the Panama Basin, as outlined in this report, was stimulated by Shipley and his coauthors (1979). They reported that in the Pacific Ocean, offshore of Panama, seismic surveys revealed the presence of bottom simulating reflectors (BSRs). Thus, the results of seismic surveys and data from the Deep Sea Drilling Project sites (DSDP) jointly with extensive investigation, thorough analysis and critical evaluation of all publicly available information, have been used as the database for the study and preparation of this report. However, because of a very limited amount of information directly relevant to the study objectives, and because DSDP sites are spread too far apart, it was necessary to extend this study into the entire Panama Basin.

The methods, scope, objectives, and format of this report are similar to six other reports already completed by Geoexplorers International, Inc. and submitted to the U.S. Department of Energy (DOE), Morgantown Energy Technology Center (METC).

The basin analysis with emphasis on those factors critical for known or inferred gas hydrate occurrences has been considered as a study approach. Although the number of DSDP sites and their sparse distribution in such a very large basin (1,200,000 km^2) is inadequate for sufficiently confident basin analysis, relatively detailed bathymetry and the seismic profiles indicate that the tectonics was, and still is, the most critical factor in the entire geological development of the Panama Basin. The major rifts and faults, active since lower Miocene time, penetrate deeply into the oceanic crust and basaltic basement. Rifts and major faults control most of the basin's geomorphology, although such control is not obvious in the volcanogenic areas. The distribution and to some extent the type of sedimentary cover, its lithostratigraphic continuity and thickness are also greatly influenced by tectonic activity.

Basin analysis has revealed that within the Panama Basin, large areas of the central and western parts of the basin appear to be unfavorable for gas hydrate formation - mainly because of thin sedimentary cover. The slopes and the terraces of the ridges may be favorable for gas hydrate formation, but at the present time there are no readily available data that could support such an assumption.

It is now apparent that the BSRs, other than those reported by Shipley et al. (1979), are also present and probably widespread in seismic profiles crossing the continental margin of Ecuador and Colombia. This could have profound implications for the assessment of gas resources associated with hydrates.

PART I

BASIN ANALYSIS

Location

The Panama Basin is located in the easternmost equatorial part of the Pacific Ocean and covers approximately 1,200,000 km^2. The territorial extent is defined by the line connecting the peninsula De Osa (Costa Rica), Galapagos Islands, Gulf of Guayaquil (Ecuador) and by the Pacific continental margins of Ecuador, Colombia, Panama, and Costa Rica (Figure 1).

Geomorphology

General geomorphology of the oceanic floor in the Panama Basin is relatively well known due to a number of seismic, magnetic, and gravimetric surveys. All these surveys were conducted in the 1960s and 1970s. The first bathymetric map of the Panama Basin, made by van Andel (1970), is shown in Figure 1. Then, Lonsdale and Klitgord (1978) published a much more detailed bathymetric map of the basin (Figure 2), which displays the relationships between structural geology and suboceanic geomorphology in the Panama Basin. The geomorphological features of the entire Panama Basin region are greatly determined by the structural setting which will be described in further parts of this report. Four major geomorophologic units constitute the Panama Basin (van Andel et al., 1971):

- Carnegie Ridge
- Cocos Ridge
- Low-lying basin, enclosed by the Cocos and Carnegie Ridges from southwest and north, and by north-south trending Coiba Fracture Zone along the longitude 83°W, and
- Eastern Panama Basin, which consists of several marginal troughs, elevated blocks and rugged deep sea floor.

The Carnegie Ridge forms the southern boundary of the Panama Basin (Figures 1 and 2). Morphologically, the Carnegie Ridge displays a simple outline trending east-west which curves slightly to the north at its eastern end. The ridge is divided into two geomorphologic subunits by a saddle between 85°W and 86°W longitudes (Figures 1 and 2).

The Galapagos Islands are located within the western part of the Carnegie Ridge. They are the two highest elevated parts of the Carnegie Ridge. The ridge slopes toward the north and south to the depths of 2,400 -

FIGURE 1, Location, Bathymetry, and Structural Setting of the Panama Basin, is located in the pocket at the end of the report.

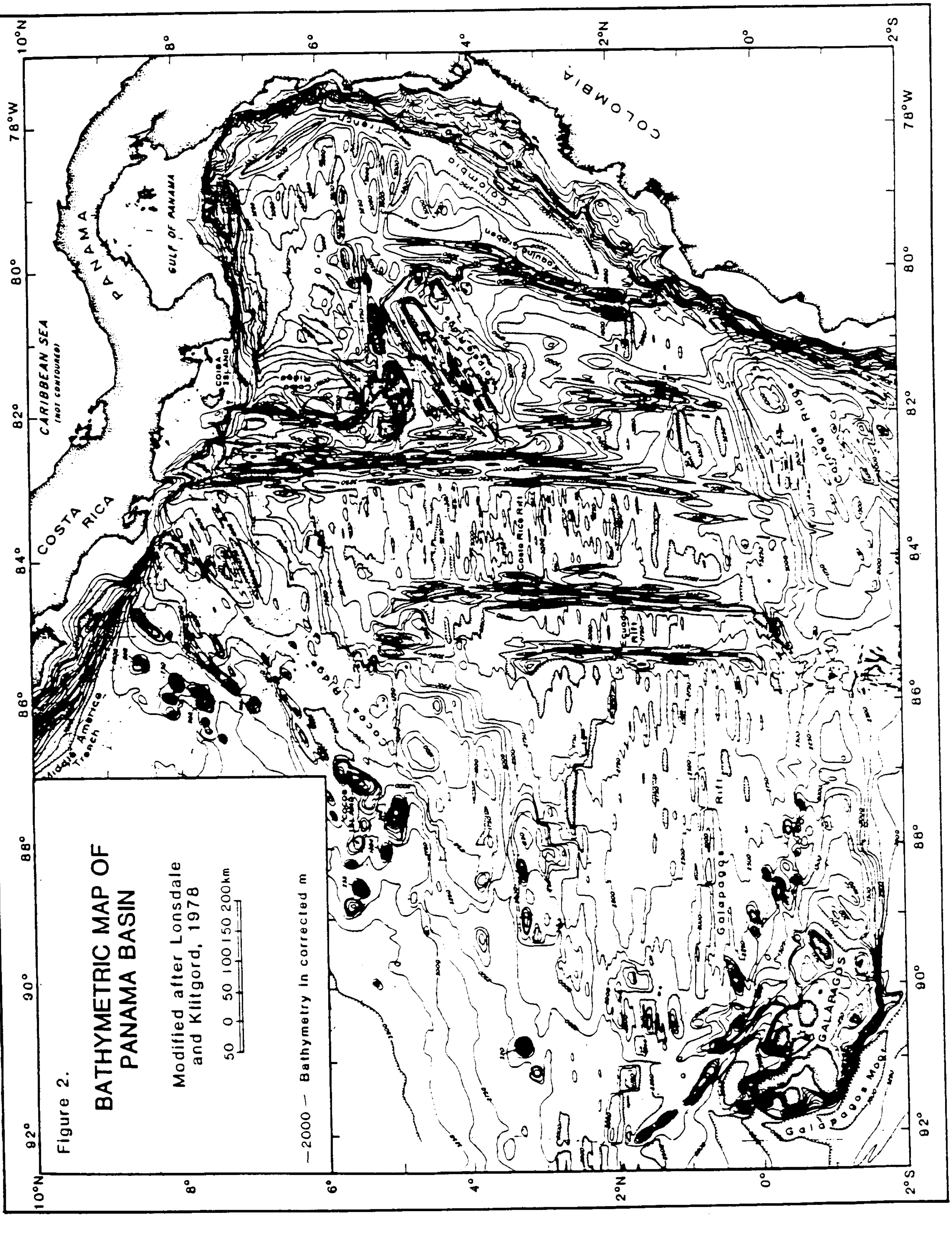


Figure 2.

BATHYMETRIC MAP OF PANAMA BASIN

Modified after Lonsdale and Klitgord, 1978

50 0 50 100 150 200km

—2000— Bathymetry in corrected m

3,000 m below sea level. The southern slopes of the Carnegie Ridge are noticeably steeper.

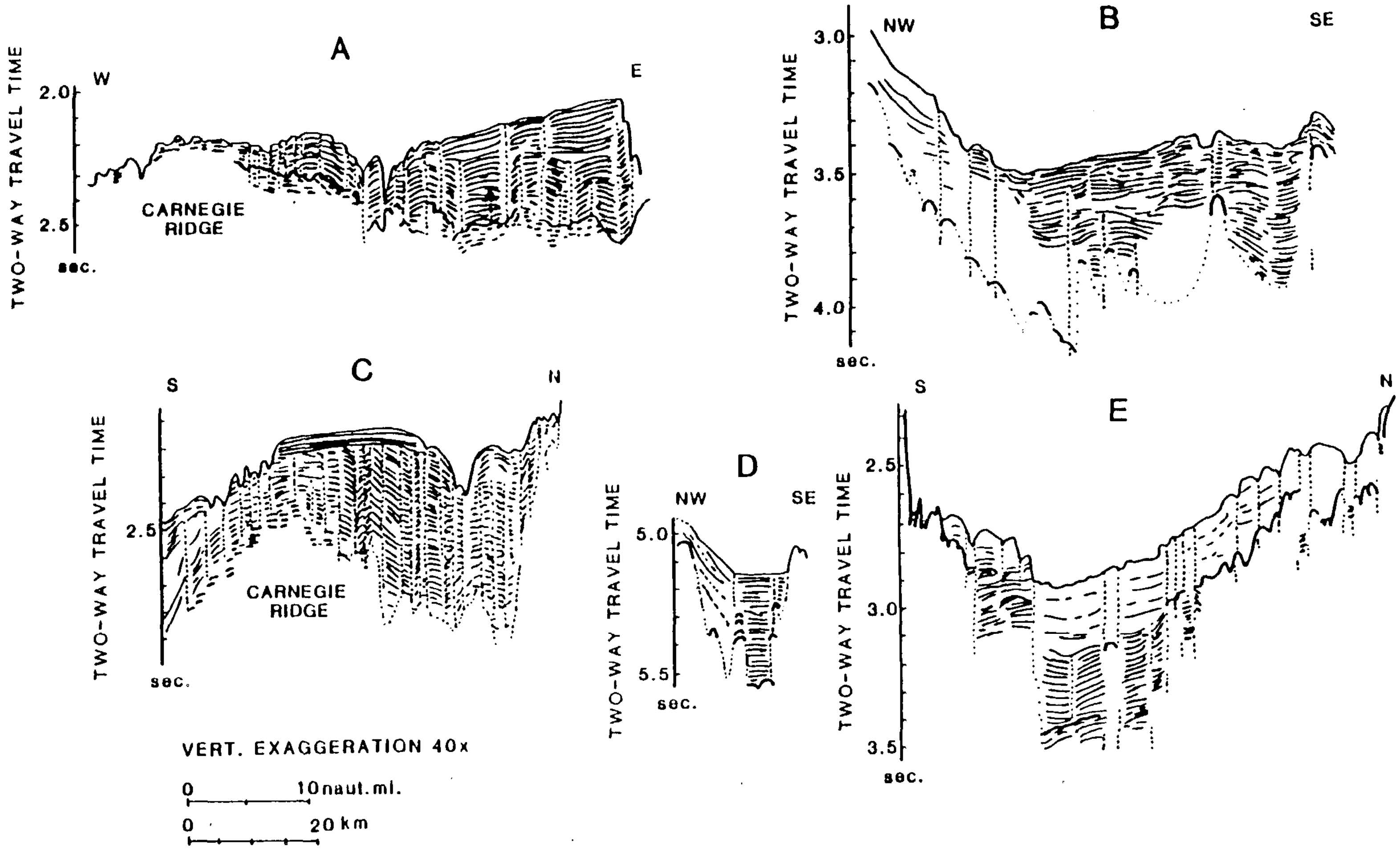
The Cocos Ridge borders the Panama Basin to the west and north. The outline of the ridge is more complex than the Carnegie Ridge. The Cocos Ridge displays alternating, north-south and west-east trending, marginal slope segments which seem to follow the major transverse fracture zones. At the northeastern end the Cocos Ridge joins the continental margin of Middle America (located northwest of the northern edge of Figure 1). The western side of the Cocos Ridge is more elevated than its eastern part. The average depth of the oceanic floor within the Cocos Ridge varies from 1,600 to 2,000 m.

Both ridges show a significant degree of similarity in terms of their geomorphologic characteristics and structural setting. The relatively flat, undulating crests are studded with small pinnacles and ledges. Seismic data pertaining to both ridges revealed horizontal stratification of sediments without any features of dynamic elevation (Figure 3). The Carnegie and Cocos Ridges are bounded by normal faults which are also evident by mostly horizontal terraces. These terraces are usually about 100 km long and 20 km wide. The uniform elevations of the terraces indicate their origin by stepwise faulting (van Andel et al., 1971).

Low-Lying Basin. The area enclosed by the Carnegie and Cocos Ridges, and the Coiba Fracture Zone (83°W longitude) represents a subregion with relatively little geomorphologic differentiation. This part of the Panama Basin deepens from 2,200 m in the west to 3,400 m in its eastern part which is topographically more diversified with north-south elongated troughs and ridges.

The remaining part of the Panama Basin east of the 83°W meridian, known as **Eastern Panama Basin** (van Andel et al., 1971), has complex relief. Except for deep water sections (3,000 - 3,600 m of water depth) the prevalent feature of this is the presence of steep sided blocks, among which the most prominent are the Malpelo Ridge and the Coiba Ridge (Figures 1 and 2). These ridges are surrounded by undulating sea floor which shows considerable roughness in many sections. The most depressed area in the Eastern Panama Basin subregion is represented by the Yaquina Graben (Figure 2) trending north-south in the area, east of the Malpelo Ridge. The oceanic floor depth in the Yaquina Graben exceeds 5,000 m. This geomorphologic and tectonic depression is the most pronounced in a series of shallower elongated troughs running parallel to the continental margin of northern South America (Figures 1 and 2).

The continental shelf within the Panama Basin ranges from 40 to 80 km, occassionally widening to approximately 100 km in the Panama Gulf.



HEAVY SUBHORIZONTAL LINES REFLECT SMOOTH, ACOUSTIC BASEMENT

PROFILES A AND C FROM THE CARNEGIE RIDGE SHOW EROSION AND A NEAR-SURFACE UNCONFORMITY
PROFILE B: DISPLAYS HEMIPELAGIC SEDIMENT OVERLYING SEMI-TRANSPARENT DEPOSITS IN THE EASTERN MARGINAL TROUGH
PROFILE D: STRATIFIED SEDIMENTS COMPLEX IN GRABEN ON COCOS RIDGE OVERLAIN BY SEMI-TRANSPARENT SERIES
PROFILE E: EROSION PRODUCTS OVERLYING STRATIFIED COMPLEX AT FOOT OF COCOS RIDGE

LOCATIONS OF THE PROFILES ARE MARKED ON FIGURE 7

Figure 3. TRACINGS OF REFLECTION RECORDS FROM THE YALOC-69 CRUISE

After van Andel et al., 1971

Structural Setting

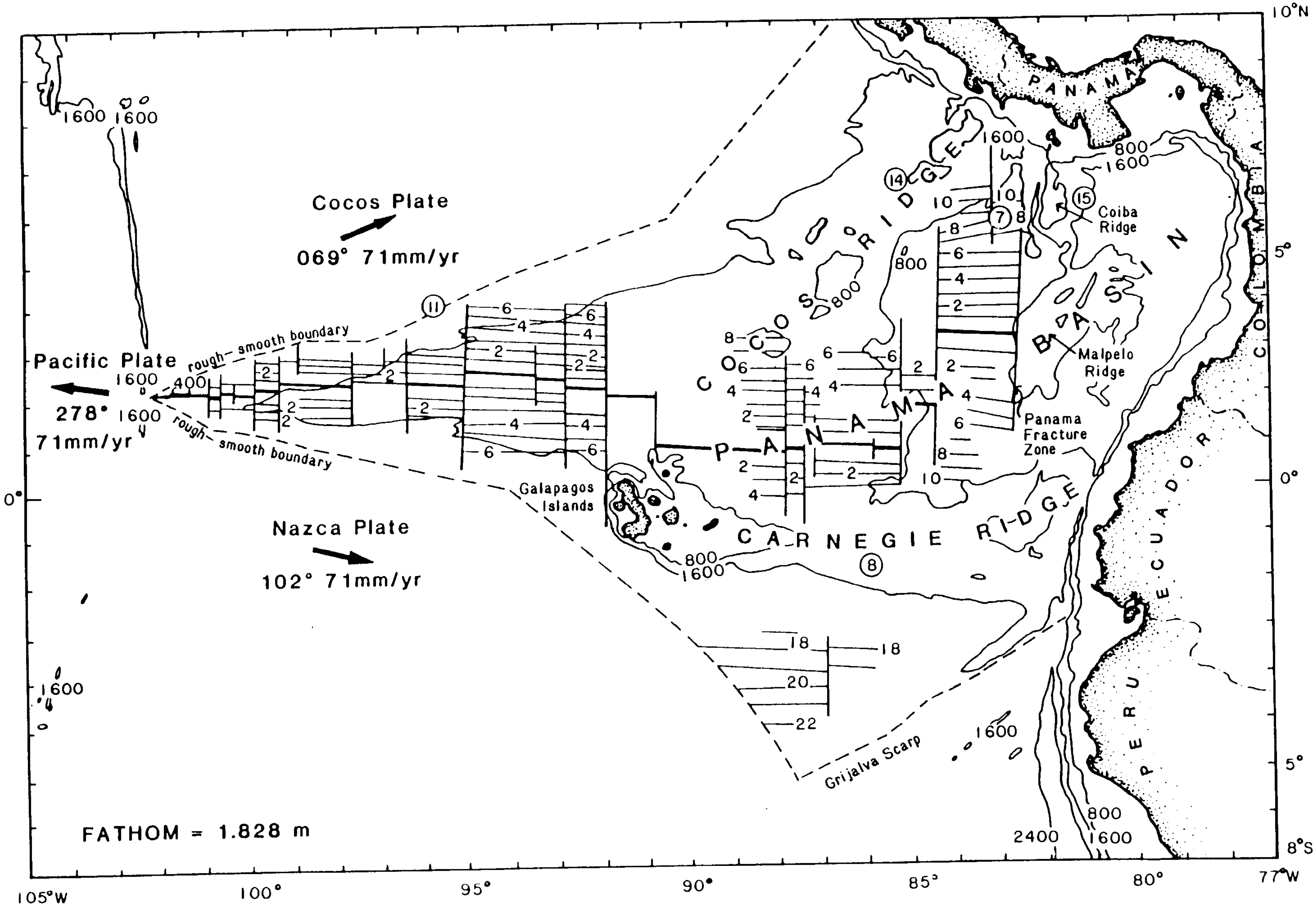
Structurally (tectonically) the Panama Basin is defined as the region bordered by Carnegie and Cocos Ridges from south and west respectively (Figures 1 and 2). The eastern and northern limits of the Panama Basin are confined to the continental margin of South America and the Isthmus of Panama (van Andel et al., 1971). A unique feature of this huge basin is that its structural development has resulted from the complex interplay of four major tectonic plates: Nazca, Cocos, South American, and Caribbean (Figure 4). It must be emphasized that the Panama Basin is one of those regions where the plate tectonic concept suggested by Morgan (1968), Le Pinchon (1968), Hacks et al. (1968) still fails to furnish adequate answers to many questions pertaining to the tectonic development of the basin.

First, more detailed insight into the structural setting of the Panama Basin was made through the data obtained from bathymetric, magnetic, gravimetric, and seismic surveys carried out by Lamont-Doherty Geological Observatory in the 1960s. Similar surveys were conducted in the 1970s by Oregon State University, Hawaiian Institute of Oceanography, U.S. Navy, University of Texas, and Scripps Institute of Oceanography, significantly increased the amount of geophysical data. These data were much needed for building the reasonable integrated concept of geological history of the Panama Basin. The advent of the Deep Sea Drilling Project (DSDP) in 1968, with several wells drilled to the basement in the Panama Basin, brought a new generation of valuable data from the region. The coring programs with the subsequent analysis of samples were designed for the verification of existing hypotheses on the Panama Basin's origin and evolution and to determine the directions of future investigations in the region.

Major structural components of the western part of the Panama Basin are the Galapagos Spreading Center (including the Galapagos Rifting Zone, Costa Rica and Ecuador Rifts) with north-south trending systems of transverse faulting zones and the Carnegie Ridge. In the Eastern Panama Basin the directions of the regional structural trends represented by fault systems are more complex. The eastern and northern limits of the Eastern Panama Basin display additionally systems of grabens and troughs. The most prominent example of such structural forms is represented by the Yaquina Graben extending north-south along the Eastern Panama Basin (Figure 2). Smaller size ridges, Malpelo and Coiba, and blocks constitute the most elevated areas of this part of the basin.

Probably one of the most intriguing features of the northern part of the Panama Basin is the lack of an active trench zone. The Middle America Trench abruptly ends in junction area of Cocos Ridge and the continental margin of Costa Rica.

The eastern margin of the Panama Basin seems to be characterized by combined transform faulting and underthrusting features. The seismicity along the Colombia-Ecuador Trench is much milder than along the Peru Trench further to the south (Jordan, 1975). The study of focal mechanisms in eastern and northern marginal areas of the Panama Basin suggest that there is no single boundary of the Nazca Plate (Pennington, 1981). Furthermore the west-east compressional motion of the plate is being accommodated along many faults striking NE-SW (Pennington, 1981). The studies of the seismicity in the Panama Basin made by Bowin (1976) and Jordan (1975) seem to indicate the prevalence of the west-east direction of the compressional movement over the north-south direction.



BATHYMETRY IN FATHOMS, ISOCHRONS IN MILLION YEARS BEFORE PRESENT, CIRCLED NUMBERS ARE AGES OF CRUST AT DSDP SITES, PLATE MOTIONS ARE RELATIVE TO TRIPLE JUNCTION, HEAVIER LINES.

Figure 4. SUMMARY DIAGRAM OF KNOWN ASPECTS OF PLATE TECTONICS IN THE PANAMA BASIN

The most coherent and widely accepted hypothesis of the Panama Basin evolution which ties together all above mentioned structural elements was presented by van Andel et al. (1971).

Galapagos Spreading Center

The Galapagos Spreading Center represents an active rifting zone extended from the Pacific-Nazca-Cocos triple junction eastward where it has been traced to the Coiba Fracture Zone (83°W latitude; Figure 4). The origin of the Galapagos Spreading Center is directly related to the breakup of the Farallon Plate about 25 m.y.B.P. and formation of the Cocos and Nazca Plates (Hey, 1977). Further motion of these plates at various rates decided to a significant degree the structural evolution of the Panama Basin. Despite some discrepancies in the results, various investigations in the region of the Panama Basin (van Andel, et al., 1971; Holden and Dietz, 1972; Johnson and Lowrie, 1972; Hey et al., 1973; Sclater and Klitgord, 1973; and others) yielded close results with respect to the accretion processes on both sides of the Galapagos Rifting Zone. A diagram summarizing these processes is shown in Figure 4. Some important conclusions can be drawn from this figure:

- The Galapagos Spreading Center consists of sections which are horizontally displaced along transform faulting systems trending north-south.

- Isochrons of the basement reveal that Panama Basin was formed during the last 6 - 12 m.y.B.P.

- Active rifting and accretion along the Galapagos Spreading Center must have started in the central part of the Panama Basin and subsequently proceeded to the west.

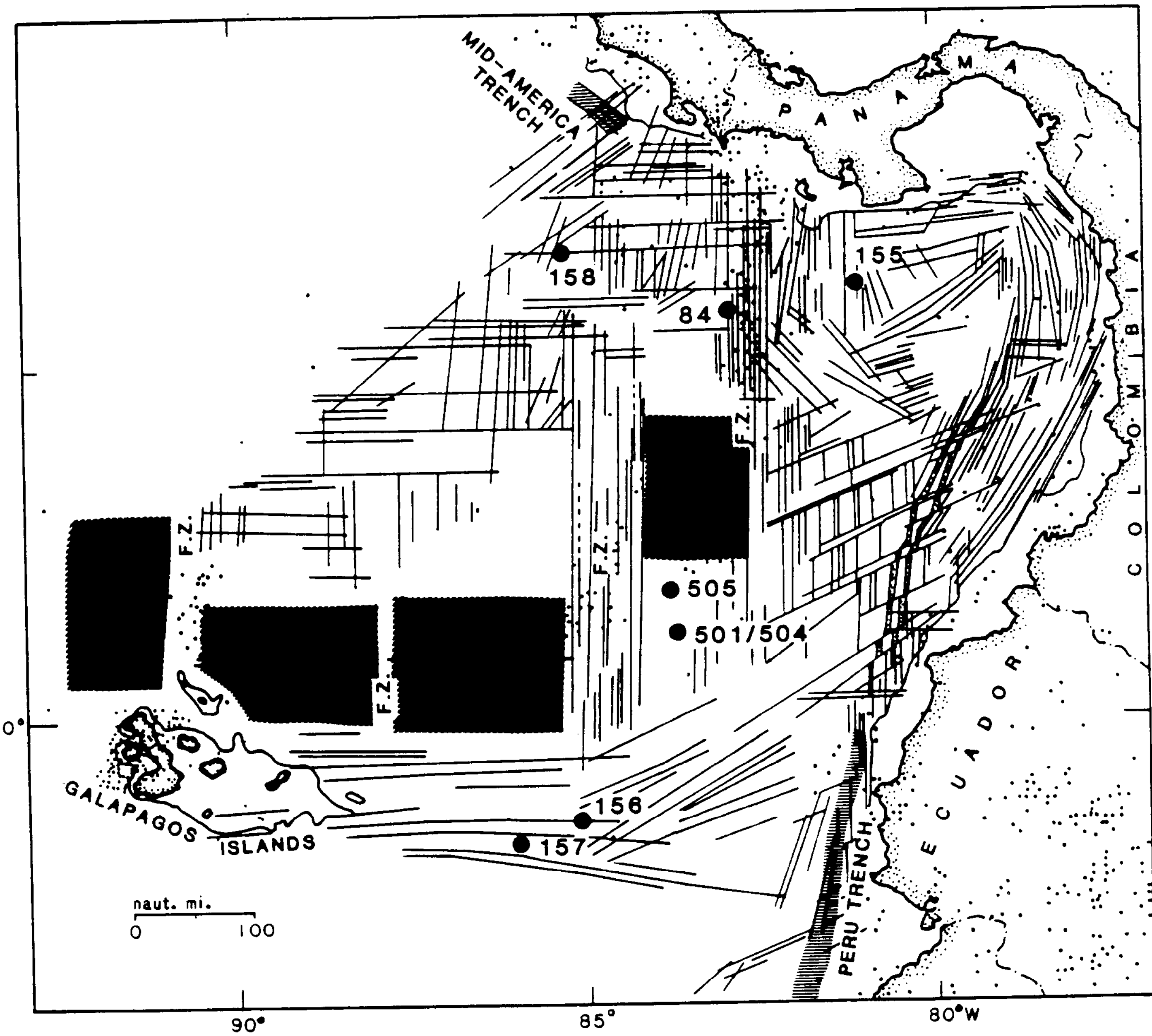
Fault Systems

The review of the seismic and other geophysical data from the Panama Basin reveals the presence of numerous fault systems. A detailed analysis of these systems was presented by van Andel et al. (1971). Using a conservative approach in delineating faults from seismic, bathymetric, gravimetric and magnetic data, van Andel and his coauthors unveiled a variety of tectonic directions which proved to be very instructive in attempts to reconstruct Panama Basin tectonic history (Figure 5).

Two categories of faults can be distinguished in the Panama Basin: major faults which resulted from major vertical displacement and minor faults with much smaller vertical displacement. The strike directions of the latter faults are not always consistent with the major faults.

With regard to the faulting systems, central and western parts of the Panama Basin are different from its eastern part (Figure 5).

Central and western parts of the Panama Basin display a relatively simple pattern of latitudinal and longitudinal faults and fracture zones. One of the major fracture zones, which is extended along the 83°W meridian, was



TRENCHES HORIZONTALLY HATCHED, INNER SCARPS OF YAQUINA GRABEN STIPPLED, GALAPAGOS RIFT ZONE SHADED, F.Z. - FRACTURE ZONE.

● DSDP SITES

· EARTHQUAKE EPICENTERS IN TIME BETWEEN 1961 AND 1969

Figure 5. DISTRIBUTION OF THE FAULTING SYSTEMS AND EARTHQUAKE EPICENTERS IN THE PANAMA BASIN

After van Andel et al., 1971

discoverd by Molnar and Sykes (1966) and confirmed by Grim (1970). This zone is expressed by a series of narrow elongated troughs and ridges and was distinguished on the basis of the earthquake distribution analysis of focal mechanisms and magnetic anomalies. The zone at the 83°W meridian was originally named the Panama Fracture Zone by the above mentioned authors. Van Andel et al. (1971) refer to the same zone as the **Coiba Fracture Zone** because it forms the western scarp of the Coiba Ridge. Another fracture zone at 85°W trending north-south is represented by the broad zone of parallel faults. The faults are closely spaced and separate short rift segments. There is considerable earthquake activity along both fracture zones. Near the **88°W** meridian, another fracture zone has been identified from the magnetic anomalies (van Andel et al., 1971). Faults in this zone are aligned with the faults in the southern section of the Cocos Ridge. Herron and Heirtzler (1967) also found a fracture zone near the 90°W meridian.

All these above mentioned fracture zones terminate against the Carnegie Ridge and there is no evidence of their extension further south.

In central and western parts of the Panama Basin, faults of smaller size constitute systems with predominant east-west directions. Very often these fault systems occur in the crests and flanks of the ridges and elevated blocks.

Eastern Panama Basin displays a much more complex fault pattern compared to the western part of the basin. A characteristic feature of the fault pattern in the eastern part of the basin is the presence of numerous faults striking in a northeast direction (Figure 5). For example northeast trending major faults appear in the eastern part of the Carnegie Ridge crest and flanks with simultaneous disappearance of the east-west oriented fault system. A northeast trending fault system also occurs between the Coiba Fracture Zone and continental margin of Central America.

One of the most noticeable structural elements of the eastern Panama Basin is the Yaquina Graben (Figure 2). This graben is developed between 2°N and 4°N as a deep trough with steep slopes which are defined by normal faults. The ridges on both sides slope gently outward through a series of faults while the outer slopes are covered with thick sediments. The graben is laterally offset along the perpendicular faults as it trends to the northeast. Van Andel et al. (1971) interpreted the Yaquina Graben as a major tensional fissure which separates two distinctly different tectonic areas. The area west of the graben comprises north-south trending faults intersected and in some instances offset by faults with northeast orientation. In the area east of the Yaquina Graben, fault series are parallel to the continental margin and form some shallow marginal troughs. These faults curve to the north imitating the continental margin and eventually intersect the continental slope of Panama (Figure 5).

All inferred faults in the Panama Basin are normal, although the existence of the reverse faults cannot be excluded as their tracing is extremely difficult using reflection seismic methods. The characteristic feature of all observed structures is their extensional nature (van Andel et al., 1971).

Ridges and Blocks

The elevated suboceanic areas are considered as ridges. They are offset by major faults and the areas between them constitute structural and geomorphologic blocks. Both ridges and blocks are the most characteristic elements in the structural setting of the Panama Basin. The origin and evolution of the ridges and blocks, together with the age of the basement, have been perceived as a major clue to understanding the structural history of the Panama Basin.

Carnegie and Cocos Ridges constitute the main part of the elevated areas in the Panama Basin (Figures 1 and 2). The Malpelo Ridge, which is of smaller size, is located in the east central part of the basin. North of Malpelo Ridge another elevated block occurs and it is often referred to as the Coiba Ridge. Besides these four ridges a number of much smaller blocks are present.

All ridges and blocks are seen by numerous investigators as having common origin. The Carnegie and Cocos Ridges were the most frequent subjects of investigation. Both ridges represent seismically active areas and show evidence of uplift along normal faults. Heath and van Andel (1973) suggested that step faults forming sides of the ridges may be the products of thermal relaxation of igneous mass of the ridges. Currently two basic hypotheses are applied to the origin of the Carnegie and Cocos Ridges: ancestral ridge hypothesis and the hot spot hypothesis:

The **ancestral ridge hypothesis** was developed by van Andel et al. (1971). Van Andel, his coauthors, and others conclude that Cocos Ridge has been split from the single ancestral Carnegie Ridge and was displaced northward along fracture zones and parallel faults (van Andel et al., 1971; Malfait and Dinkelman, 1972; Heath and van Andel, 1973; Rea and Malfait, 1974). According to this hypothesis an ancestral Carnegie Ridge collided with South America approximately 25 m.y.B.P. Presumably as a result of this collision split-off fragments of the Carnegie Ridge drifted to the north and formed Cocos Ridge. Other blocks can also be considered as the remnants of split-off fragments of the Carnegie Ridge. Active rifting processes originated in the Galapagos Spreading Center are primarily responsible for the displacement of parts of the ancestral Carnegie Ridge. In the area west of the Coiba Fracture Zone, spreading started about 10 m.y. ago. Initially it started in the eastern part of the rifting zone and gradually progressed to the west. Van Andel and other investigators have not found evidence of compressional features in the Carnegie Ridge. The same authors also concluded that major rift zone must be migrating northward.

The **hot spot hypothesis** on the origin of the Carnegie and Cocos Ridges was presented by Morgan (1971), Holden and Dietz (1972), and Hey et al. (1977). These authors presented evidence from recent plate motions that Cocos and Carnegie aseismic ridges are hot spot traces. The analysis of plate motion predicted that if the Galapagos Islands were hot spots, there should be aseismic ridges trending away from the islands in the directions very close to those known as the of Carnegie and Cocos Ridges. Thus, according to the proponents of the "hot spot" hypothesis, Carnegie and Cocos Ridges were formed by outpourings of basalt basement from the Galapagos hot spots onto the Cocos and Nazca plates. Subsequently the ridges must have been separate entities throughout their existence.

Sclater and Klitgord (1973) have objections to both hypotheses. Their objections toward the ancestral ridge hypothesis are based on the studies of magnetic anomalies. Sclater and Klitgord found asymmetric evolutionary patterns on both sides of the Galapagos Spreading Center. This asymmetric development of the basin is in contradiction with van Andel's hypothesis. Similar objection pertains to the hot spot hypothesis. It seems, however, that both hypotheses are viable if asymmetric rifting development is assumed.

Pacific Continental Margins of Panama and Colombia.

The structural nature of the Panama and Colombia continental margins is one of the important and still not fully determined features of the Panama Basin. Contrary to the margins with active subduction zones of the Middle America Trench and Peru Trench extending in northern and southern direction respectively, the continental margin within the Panama Basin represents a relatively inactive tectonic region. According to van Andel et al. (1971), the northern edge of the Panama Basin does not show evidence of subduction or underthrusting. The marginal trough is further considered by van Andel and his coauthors as a simple downfaulted form filled with sediment. Morgan (1968), Hayes and Ewing (1970), and Lowrie (1978) suggested the idea of a buried trench that should exist south of the Panama continental margin (buried Panama Trench). The relict subduction zone was believed to be located south of the Gulf of Panama (Morgan, 1968). The reasoning in this concept was driven by the fact of the gap in age between the oceanic crust in eastern Panama, dated as Upper Cretaceous (Case, 1964), and the upper Tertiary lithostratigraphic sequence (Lonsdale and Klitgord, 1978) of the adjacent Pacific Ocean floor, which requires the crustal consumption or dislocation. Houtz (1974) estimated the sediment thickness in the buried Panama Trench to reach 2,500 m. The idea of the Panama Basin structural development promoted by van Andel and his coworkers explains the cessation of active subduction in the Panama Trench by progressive blockage and plugging the subduction zone by northward migrating Cocos, Coiba and Malpelo Ridges. Spreading of the oceanic crust which halted about 10 m.y. ago (Lonsdale and Klitgord, 1978) was followed by underthrusting of Panama which is believed to have occurred as a result of Caribbean and Panama (Nazca?) plate convergence. This event led to formation of the Panama Isthmus (Bandy and Casey, 1973).

The characteristic feature of the Eastern Panama Basin is significantly reduced tectonic activity compared with the zone of the Peru Trench. The boundary of the South American plate apparently continues northward from the Peru Trench through western Colombia into the Caribbean region. A predominant feature of the easternmost part of the Panama Basin is the presence of fault-bounded marginal troughs. Similar troughs were identified on land in the coastal zone of the Pacific Ocean of Colombia (Case et al., 1971).

Panama Isthmus

The Panama Isthmus forms a natural northern closure of the Panama Basin. Although there is still no firm consensus among scientists as to the origin and tectonic position of the Isthmus, the time of its final uplift about 5 m.y.B.P. is generally accepted.

The structural characteristics of the eastern part of Panama Isthmus are better known than those of its western part. All geological investigations of this structural unit were based mainly on the results from the gravimetric surveys and structural studies. The Panama Isthmus consists of volcanic, intrusive igneous and sedimentary rocks. The basement which outcrops in vast areas of eastern Panama is of pre-Eocene age (Terry, 1956). The sedimentary basin axes are concordant with the extention of the Isthmus. The sediments are of Eocene to Miocene age.

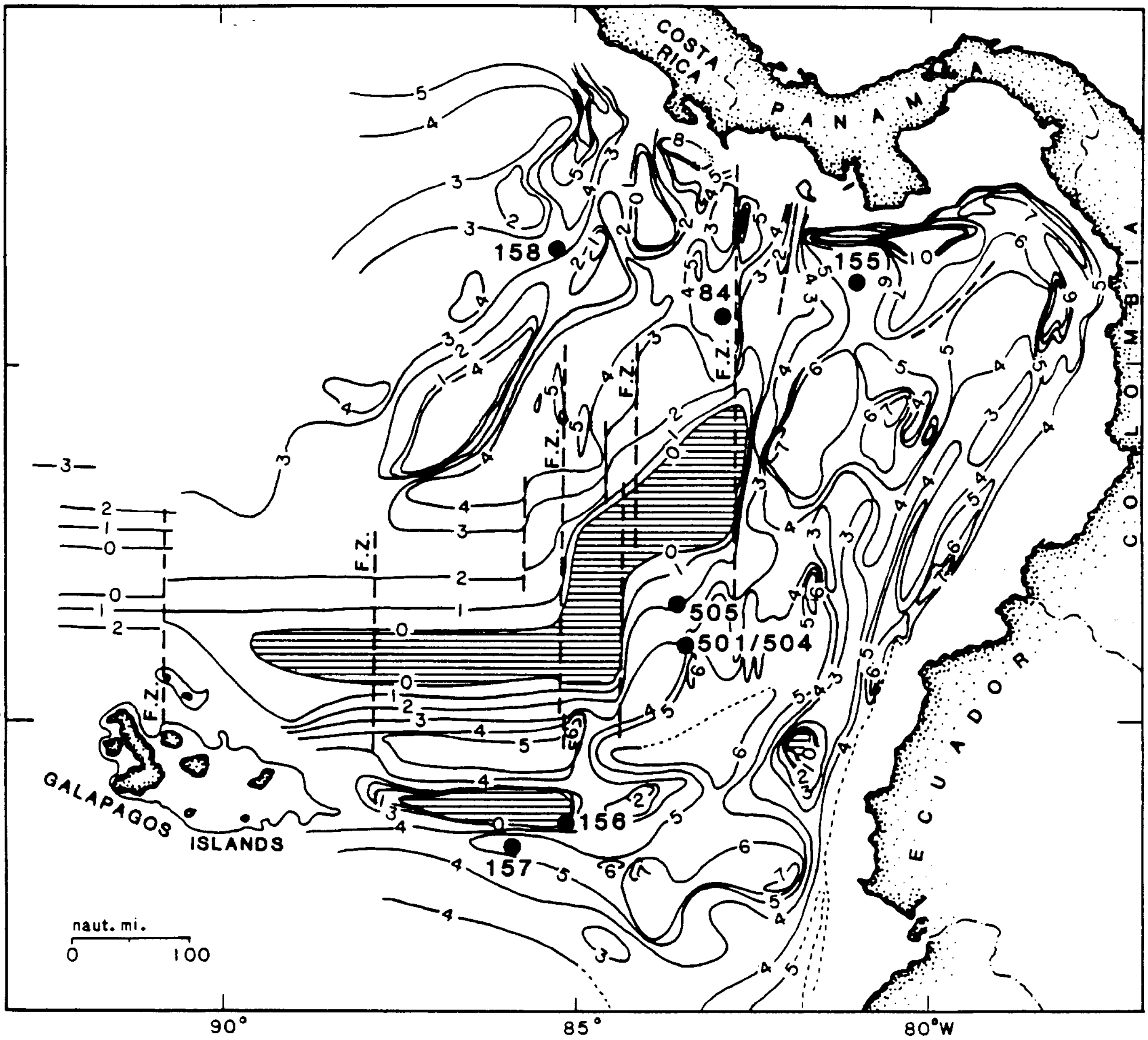
Lloyd (1963) suggested that the evolution of the Isthmus started in Jurassic-Cretaceous time as a series of volcanic arcs forming an island arc by Eocene time. Plate tectonic studies made by various investigators (e.g. Le Le Pichon, 1968) suggest that the movements of the Caribbean and Pacific Plates took place in opposite directions. As a result of this, the trench structures were produced on both sides of the Isthmus (Hayes and Ewing, 1976). During the ensuing episodes of the opposed relative plate motions, the Panama Isthmus was uplifted. Yet, the other investigations suggest that the sigmoidal shape of the Isthmus resulted from compressive movements between Central and South America (Lloyd, 1963).

Sediment Distribution

The initial studies of the sedimentation patterns in the early 1970s in the Panama Basin had been made by van Andel et al. (1971) and were based on seismic, magnetic, and gravimetric data. Since 1968 when the Deep Sea Drilling Project (DSDP) was started, the previously developed concepts could be checked and verified through the results of the direct analysis and observations from the DSDP information.

The sedimentation pattern in the Panama Basin is principally defined by its tectonic history and high biogenic production in the region. Deposition of the terrigenous material has been relatively minor in the entire Panama Basin. Also, the postdepositional redistribution of sediment was limited to the elevated ridges.

The general regional sediment distribution in the Panama Basin is shown after van Andel et al. (1971) in Figures 6 and 7. The map of sediment isopach shows thinning trends toward the elevated sections of the basin. The center of the Galapagos Rifting Zone as well as parts of the major ridges and elevated blocks are free of sediment. To the contrary, the zones with the thickest sedimentary sequence can be found in the marginal troughs of the basin (Figures 6 and 7). In general, thickness of the sedimentary cover in the Panama Basin varies from 0 to 600 m, occasionally reaching 1,500 m. The sediment distribution pattern differs basically between deeper and elevated parts of the basin. Configuration of the basement seems to be an important



NOTE: APPROXIMATE THICKNESS OF SEDIMENT (IN METERS) CAN BE OBTAINED BY MULTIPLYING THE GIVEN TIME VALUES BY 80

HORIZONTALLY HATCHED AREAS REPRESENT YOUNG CRUST ALONG THE GALAPAGOS RIFT ZONE OR ERODED CRESTS OF THE COCOS AND CARNEGIE RIDGES

F.Z. - FRACTURE ZONE ● DSDP SITES

Figure 6. ISOPACH MAP OF SEDIMENT ABOVE ACOUSTIC BASEMENT IN TENTHS OF SECONDS, TWO-WAY TRAVEL TIME

After van Andel et al., 1971

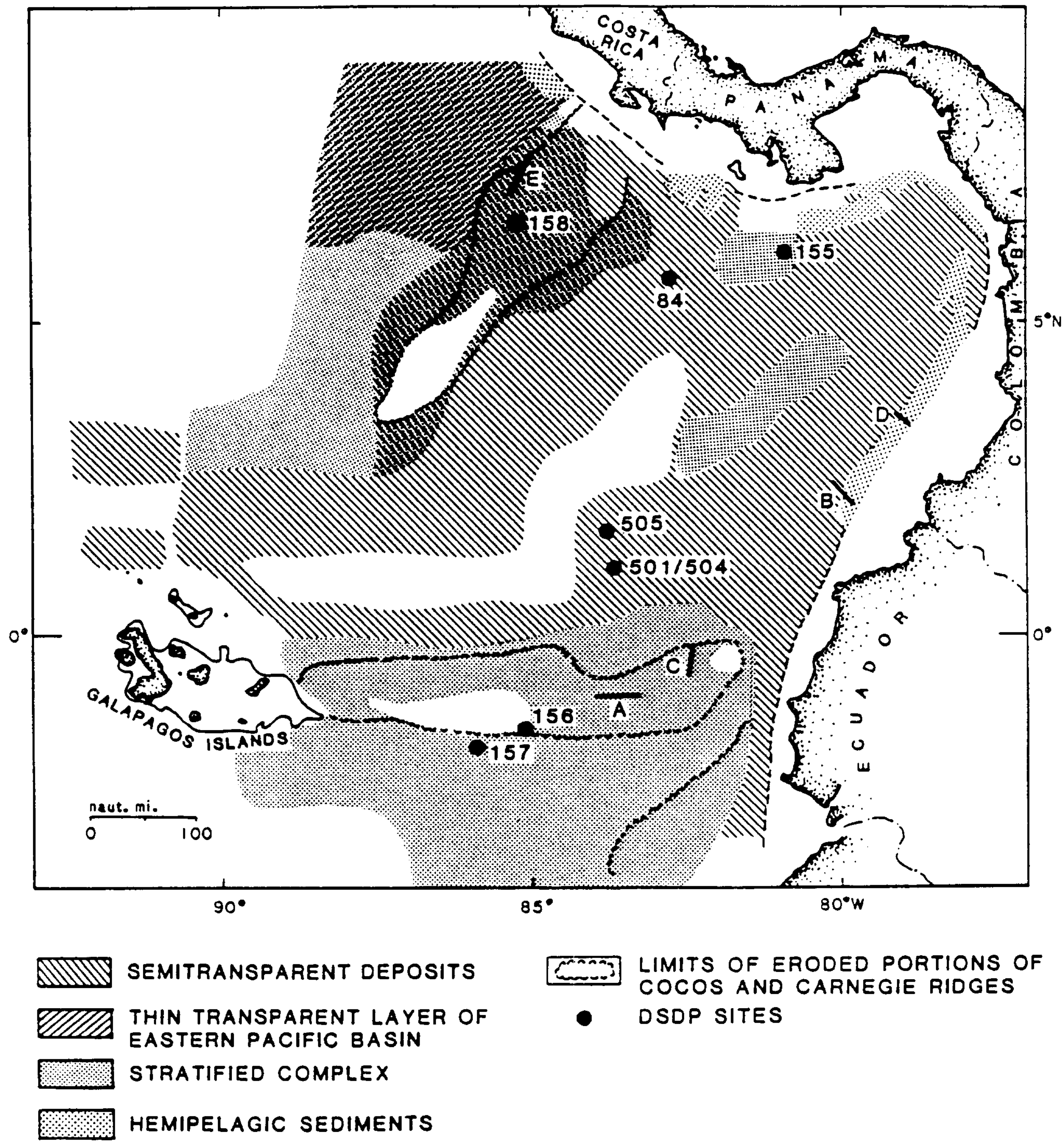


Figure 7. **DISTRIBUTION OF ACOUSTICALLY DEFINED SEDIMENT TYPES IN THE PANAMA BASIN**

After van Andel et al., 1971

factor in the sediment distribution. Some examples showing this latter relationship are presented on Figures 8, 9, 10, 11, and 12. Despite the currently continued scientific disputes on the nature and character of the basement in the Panama Basin, the basement determined by acoustic measurement has been identified in most of the region. Two types of the basement can be distinguished. First the rugged type, which is assumed to be of volcanic origin as it strongly resembles the volcanic areas of the young Galapagos Rift Zone. This type of basement is widespread in the deeper parts of the basin. The characteristic feature of this type of basement is the presence of pinnacles, ridges and rough subbottom surfaces. Second, the smooth type of basement has been found only on the Cocos, Carnegie, Malpelo and Coiba Ridges. In the entire Panama Basin the upper sediment surface reflects well the configuration of the basement.

Van Andel et al. (1971) distinguished three main sedimentary sequences in the Panama Basin based on seismic data (Figures 3 and 6):

1. Thinly and evenly stratified sediments which occur on all high elevated blocks. This sequence is best developed on the Carnegie Ridge. It also occurs on the Cocos Ridge in the lower part of the sedimentary sequence.

2. The stratified sequences in the troughs near the Panama and Colombia continental margin. In these sediments, however, bedding is much less even and it is usually interrupted by small unconformities or cross-stratification. These sequences frequently overlie seismically semitransparent deposits. They were identified by van Andel et al. (1971) as hemipelagic deposits perhaps containing turbidites.

3. Thick semitransparent deposits featuring widely spaced fuzzy reflectors are characteristic of deeper parts of the Panama Basin with the exception of the young floor of the Galapagos Rift Zone. This sequence often overlies unconformably the stratified complex of the Cocos Ridge and it may be the equivalent of the thin transparent strata which overlies unconformably the stratified complex on the Carnegie Ridge.

The investigation of the above mentioned sedimentary sequences on the ridges enabled van Andel and his coworkers (1971) to reveal the evidence for frequent periods of the suboceanic erosion. The stratified complexes in small grabens within the Cocos Ridge suggest that these sediments were deposited prior to faulting and possibly prior to the uplift of the ridge. The younger sedimentary sequence on the Cocos Ridge was deposited on the unconformity. This unconformity in the central part of the ridge is a product of the suboceanic erosion, volcanic activity and slumping which removed most of the sediment. The eroded material was deposited on both sides of the ridge covering the stratified complexes at the foot of the tectonic and geomorphological escarpments.

In the structural development of the Carnegie Ridge the depositional and erosional stages can be distinguished. In many profiles the unconformities within the stratified complex have been found at approximately one third of the sediment mantle thickness above the basement. Contrary to the Cocos

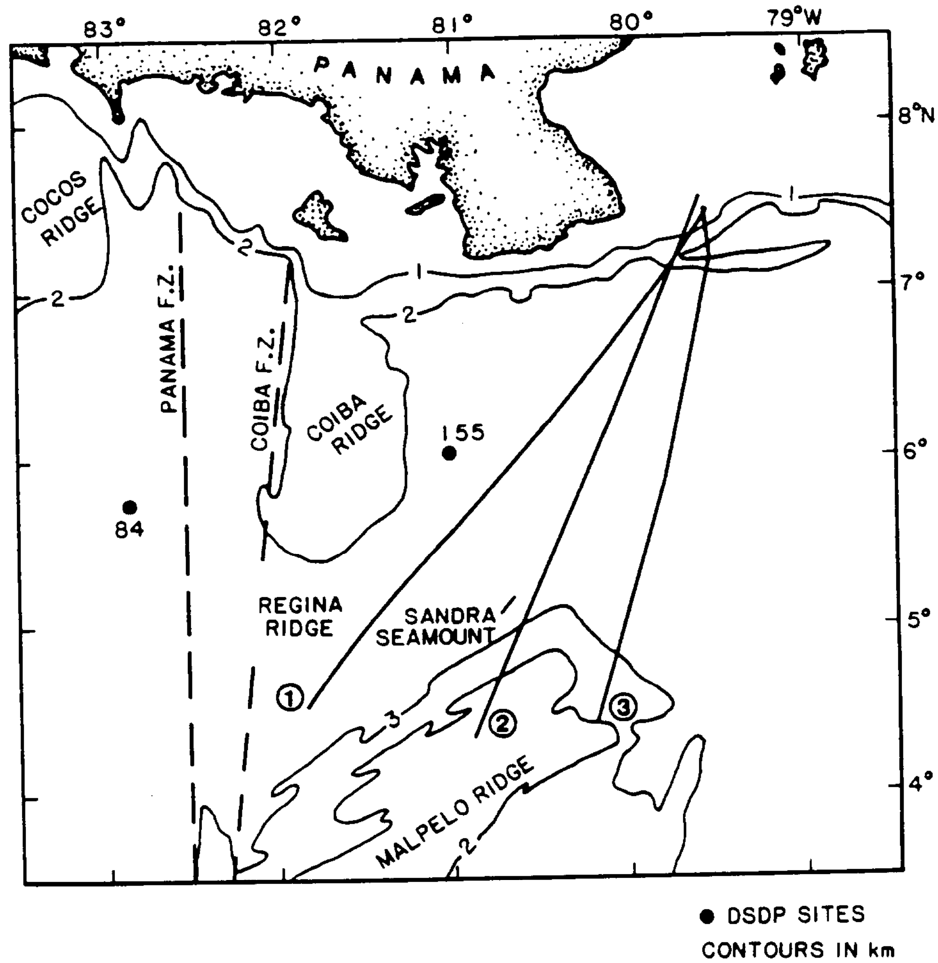
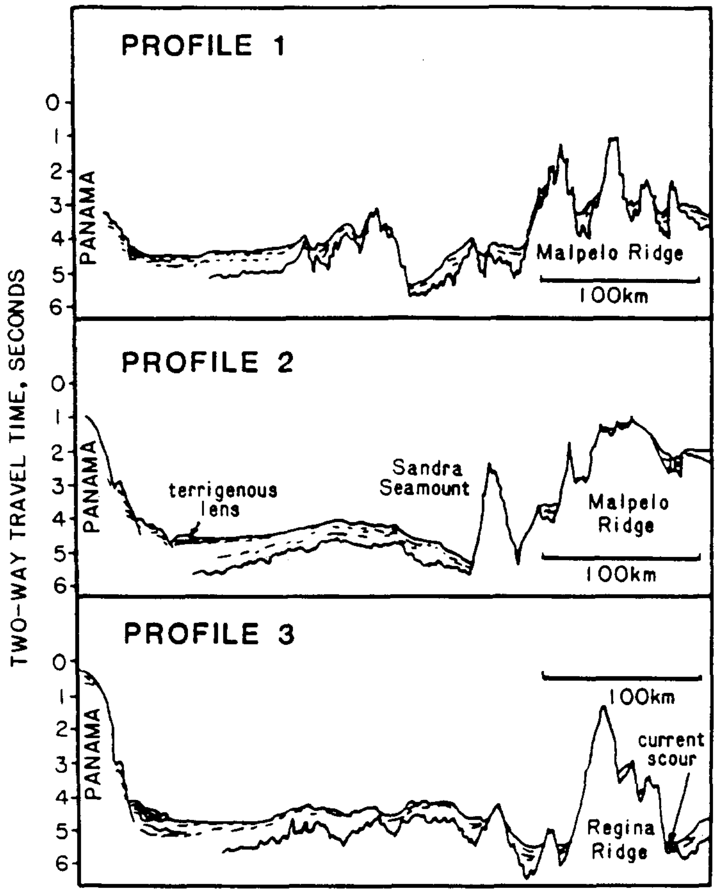


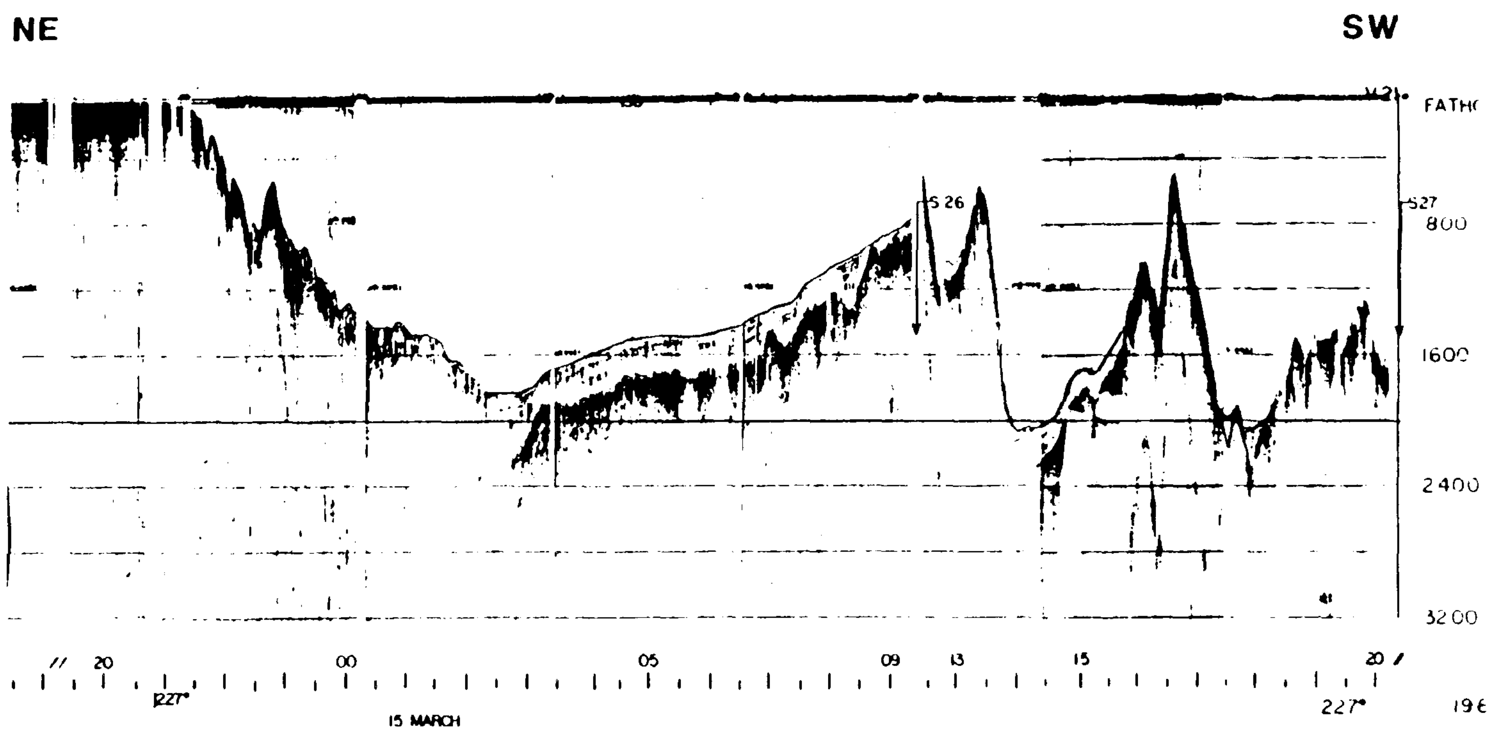
Figure 8. MAP OF TRACK LINES FOR PROFILES SHOWN ON FIGURE 9



TRACK LINES ARE SHOWN ON FIGURE 8

Figure 9. **PROFILES BETWEEN PANAMA SLOPE AND MALPELO RIDGE SHOWING STRUCTURAL RELATIONSHIP BETWEEN THE BASEMENT AND SEDIMENTARY COVER**

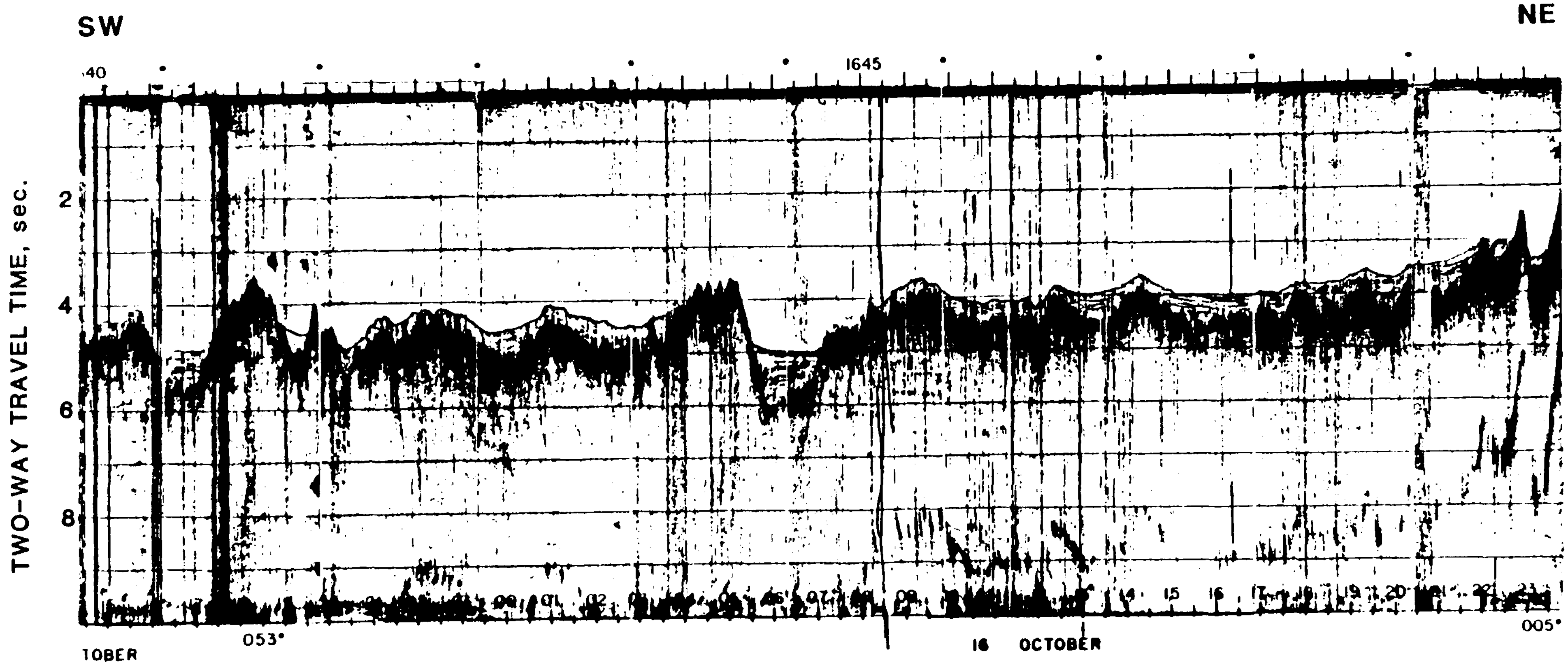
After Lonsdale and Klitgord, 1978



FOR TRACK-LINE OF THIS PROFILE SEE FIGURE 1

Figure 10. PANAMA BASIN – AIR GUN SEISMIC LINE V2104 SHOWING TOPOGRAPHY OF THE BASEMENT AND ITS RELATIONSHIP TO THE SEDIMENTARY COVER

FIGURE 11, Panama Basin -- Air Gun Seismic Profile V2809 Showing Relationship Between the Basement Topography and Sedimentary Cover, is located in the pocket at the end of the report.



FOR TRACK-LINE OF THIS PROFILE SEE FIGURE 1

Figure 12. PANAMA BASIN – AIR GUN SEISMIC PROFILE C1111 SHOWING RELATIONSHIP BETWEEN TOPOGRAPHY OF THE BASEMENT AND SEDIMENTARY COVER

Ridge, the lower unconformity within the stratified sequence separates two periods with similar sedimentological regimes. In the central part of the Carnegie Ridge there is a zone free of sediment (Figure 6). The sediment was removed by suboceanic erosion. The erosion apparently takes place today. Eroded material was found along the north edge of the Carnegie Ridge. The flat topography of the ridge crest seems to suggest that oceanic current erosion is the main erosional factor instead of the slumping or volcanic activities.

The channeling processes on the slopes of the major ridges have been described in the pertinent literature (Heath and van Andel, 1973).

Sedimentation and Lithostratigraphy

Presently available data is not sufficient for detailed lithostratigraphic correlation of the sedimentary sequence in the Panama Basin. The few holes drilled in the region and relatively thin sedimentary cover in most parts of the basin are the main impediments to stratigraphic determination and correlation. In this case, the study of the contemporary lithofacies jointly with the data from the eight DSDP sites in the region and presently accepted concepts pertaining to the tectonic development of the Panama Basin seem to be a reasonable approach for determination of the lithostratigraphic relationships in the basin.

The Panama Basin represents the equatorial region of unusually high biological production. Upwelling oceanic currents bring nutrient-rich deep water to the near surface which results in high production of plankton. Subsequently, the pelagic sediment is formed in the region; it is primarily composed of the calcareous and siliceous remnants of the planktonic microorganisms. Lithogenic components such as clay and quartz of continental origin constitute a minor fraction of the sediment in the Panama Basin and are probably limited to its northern and eastern margins.

An important factor affecting the presence and the rate of sedimentation of carbonates is the ratio of the calcium carbonate supply and its dissolution in much colder deep sea water. The balance of the two processes (supply and dissolution) defines the carbonate compensation depth (Berger and Winterer, 1974), which separates zones undersaturated and supersaturated in calcium carbonate. In the Panama Basin, high surface productivity of calcium carbonate mostly overrides the dissolution of the carbonate particles (Heath and van Andel, 1973). It appears that the distribution of the calcareous sediments in the basin is mainly controlled by the bathymetry of the sea floor. An excellent representation of the latter statement was given by Moore et al., 1973 (Figure 13). The same authors presented the map of distribution of total sediment less than 2 microns in diameter (Figure 14). Again the correlation between distribution of the fine sediment and bottom topography can be observed. Fine sediments are found in bathymetric depressions.

In addition to carbonates, the flux of the biogenically formed particles sinking through the water column consists of opal and cellular amorphous organic matter (Berner, 1979). The process of dissolution of opal is primarily controlled by a temperature and therefore it is intensified in shallow waters (Hurd, 1972). Interesting and unique results of the contemporary biogenic

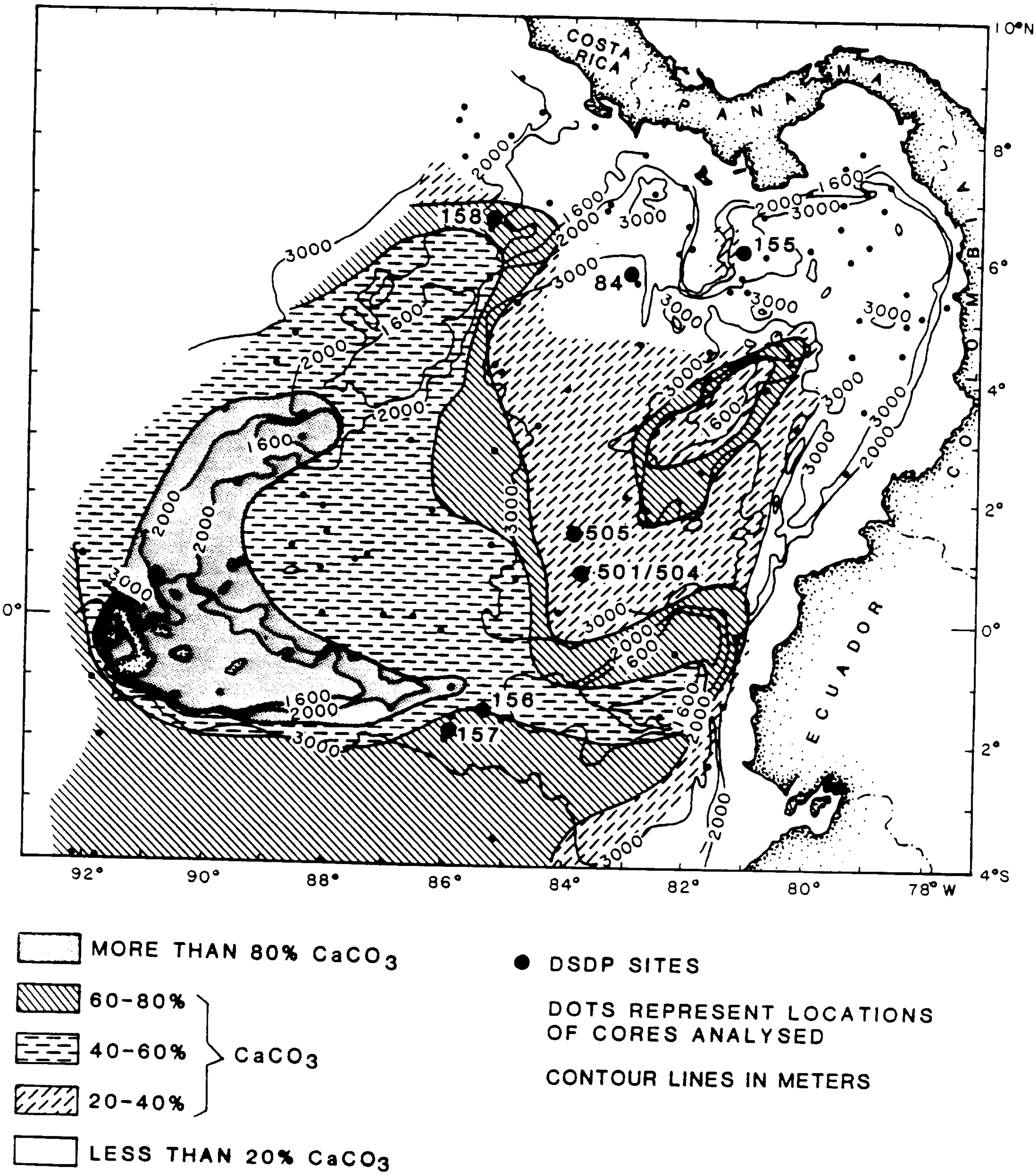


Figure 13. PERCENTAGE OF CALCIUM CARBONATE IN SURFACE SEDIMENTS OF THE PANAMA BASIN

After Moore et al., 1972

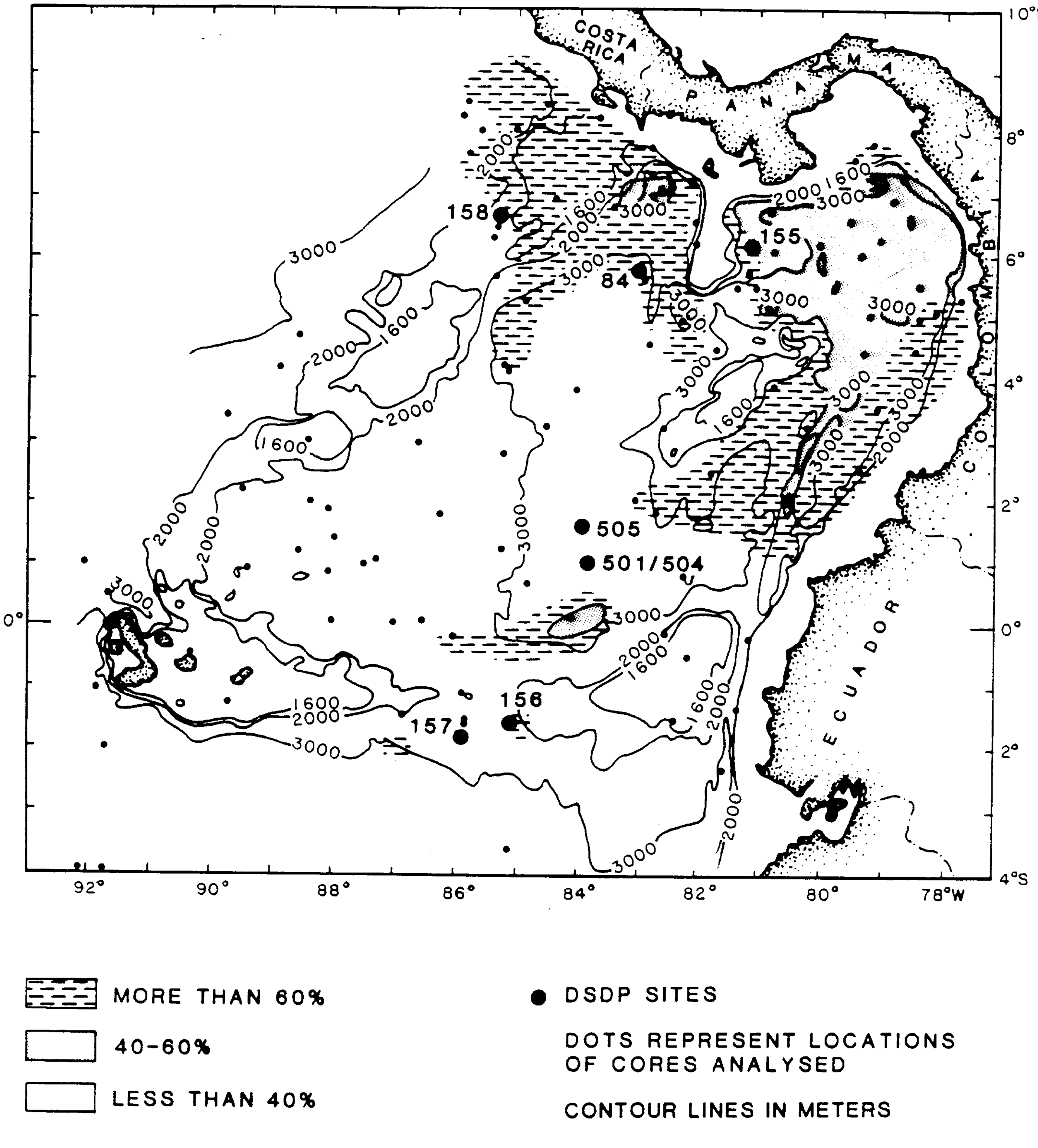


Figure 14. DISTRIBUTION OF SURFACE SEDIMENTS OF LESS THAN 2μ FRACTION IN THE PANAMA BASIN (as a percentage of sediment)

carbonate, opal, lithogenic and organic matter fluxes were published by Honjo et al. (1981) for the survey station located in the north central part of the Panama Basin (5°21'N latitude, 81°53'W longitude). Average ocean depth at this station is 3,856 m. The above mentioned fluxes were measured with use of six Parflux Mark II sediment traps. The total flux of biogenic and lithogenic materials accounted for 114.1 to 179.6 mg $\cdot$ $m^{-2} \cdot day^{-1}$(Table 2, Figure 15). Assuming the density of the sediment equal to 1.9 g $\cdot cm^{-3}$, the rate of sedimentation in the area would be around 34 m $\cdot$ $m.y.^{-1}$. Biogenic materials found by Honjo et al. (1982) constituted 40% to 80% of the sediment flux (Table 2; Figure 15).

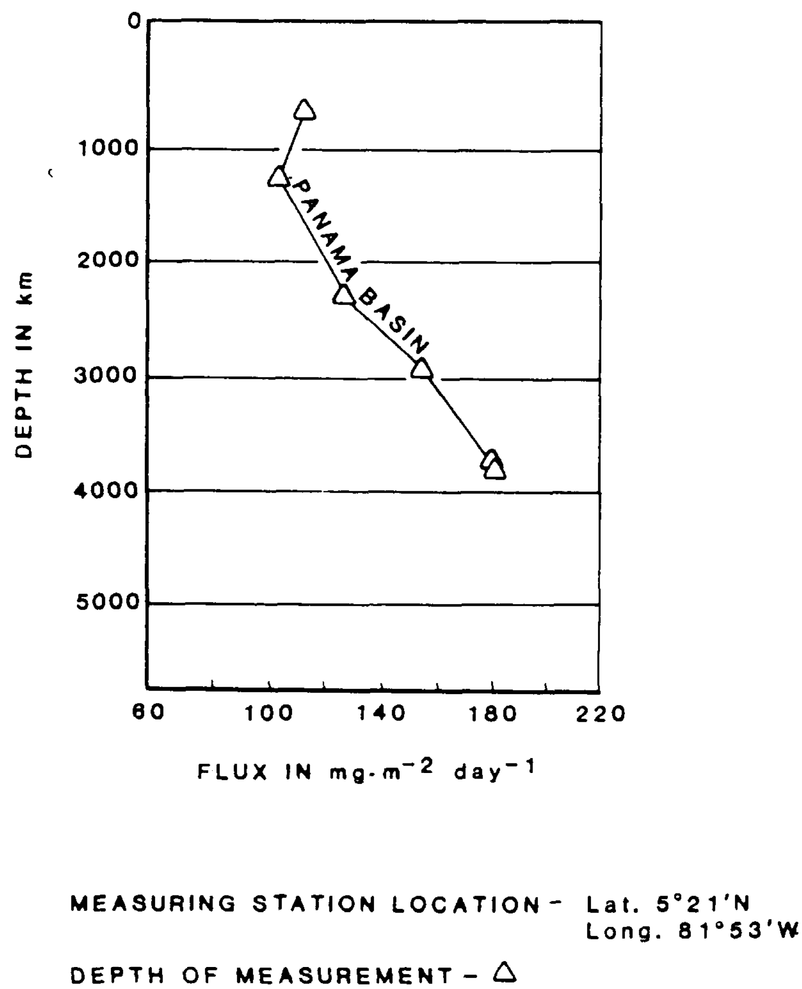


Figure 15. SEDIMENT MASS FLUX IN THE PANAMA BASIN

Modified after Honjo et al., 1982

TABLE 2.

THE SEDIMENT FLUX (mg x m² x day⁻¹) AND CONTRIBUTION OF BIOGENIC AND LITHOGENIC MATERIAL IN THE PANAMA BASIN SURVEY STATION*. After Honjo et al., 1982.

Station and water depth, m	Mass flux mg x m² x day	Biogenic %	Lithogenic %
667	114.1	81.1	18.9
1,268	104.5	80.1	19.9
2,265	125.1	73.3	26.7
2,869	158.0	68.7	31.3
3,769	179.3	58.2	41.8
3,791	179.6	58.9	41.1
Sediment	NA**	41.1	58.9

* The station was located at longitude 81°53'W and latitude 5°21'N.
** NA - not available

Honjo and his coworkers (1974) divided the suspended sediment in the oceanic water column into combustible, acid-soluble and non-combustible components. It was found that with increasing water depth the suspended material shifted toward non-combustible type of sediment (Table 3). This

TABLE 3.

FRACTIONATION OF SEDIMENTS TRAPPED IN WATER COLUMN AND OCEANIC FLOOR SURFACE IN THE PANAMA BASIN SURVEY STATION. After Honjo et al., 1982.

Station and depth, m	Soluble carbonate, %	Combustible %	Non-combustible %
667	36.1	22.5	41.3
1,268	39.2	19.2	41.6
2,265	35.9	17.0	47.1
2,869	32.2	17.0	50.8
3,769	25.2	13.6	58.2
3,791	26.1	16.5	57.4
Sediment	21.5	13.0	65.5

Soluble material is that which dissolved in 0.5 N acetic-acid at 15°C; consists mainly carbonate,
Combustible material is that which was lost by combustion at 550°C for 4 hours; consists mostly of organic material
Non-combustible material consists mainly of clay, quartz, feldspar.

means that relative contribution of organic matter to the total amount of sediment flux decreases with depth.

Flux of the biogenic material can be of three types: carbonate, biogenic, opal, and organic matter.

Carbonate flux in the Panama Basin includes planktonic foraminiferal tests, coccoliths, pteropod shells and other miscellaneous hard tissues. The flux of foraminiferal tests of size between 100μ and 1,000μ constituted 15 to 50% of the total carbonate flux and even within a narrowed fraction range (63μ to 1,000μ) it is correlated positively with the total carbonate flux (Honjo et al., 1982). Coccoliths contribute 20 to 40% of the total carbonate flux in the Panama Basin. Deep water in the basin is undersaturated in carbonate. Therefore the sedimentation of the coccoliths must occur with particles larger than individual cells as fecal pellets or aggregates to prevent their total dissolution before deposition.

Biogenic opal flux originates from radiolarian skeletons and spicules, diatom shells, diatom frustules and silicoflagellate skeletons. Measured values of the opal flux in vertical profile at the survey station in the Panama Basin varied from 23 to 80 $mg \cdot m^{-2} \cdot day^{-1}$ (Honjo et al., 1982); the fluctuations were probably caused by the horizontal transport of sediment. Despite the fact that oceanic water in the Panama Basin is undersaturated with opal at all depths, the radiolarian shells caught in the measuring traps did not show signs of their extensive dissolution.

Organic matter flux in the water column of the Panama Basin consists of amorphous particles including free cells of fecal pellets, zooplankton carapaces and molts. Decrease in the amount of the organic carbon measured at the Panama Basin survey station sediments was revealed in the mesopelagic layers (Table 4). Analysis of the flux sediment material also showed that the bulk of the the organic carbon is in amorphous fine particles. At approximately 100 m above the ocean bottom the flux of organic carbon amounts to 10.5 $mg \cdot m^{-2} \cdot day^{-1}$ (water depth at the measuring station was about 3,856 m). The organic carbon constituted 5.2% of the sediment sample. Bottom sediment at the same location contained 1.7% organic carbon showing unusually high net sedimentation rate of this component in the basin.

Tables 4 and 5 show the results of the analysis of the flux of biogenic constituents of the Panama Basin survey station.

TABLE 4.

THE FLUX OF BIOGENIC CONSTITUENTS AT THE PANAMA BASIN SURVEY STATION*. After Honjo et al., 1982.

Station and depth, m	Flux, mol m^{-2} day^{-1}					Atomic ratio					
	C_{carb}	C_{org}	N	Si	P	C_{org}:N	C_{org}:P	C:Si	C_{carb}:Si	C_{org}:Si	Si:N
PB 667	393	1,048	109	440	3.3	9.6	318	3.3	0.9	2.4	4.0
1,268	390	746	85	403	3.3	8.8	226	2.8	1.0	1.9	4.7
2,265	428	755	89	442	3.6	8.5	210	2.8	1.0	1.7	5.0
2,869	484	905	102	582	-	9.9	-	2.4	0.8	1.6	5.7
3,769	430	948	104	578	3.6	9.1	263	2.4	0.7	1.6	5.6
3,791	447	875	78	537	4.1	11.2	213	2.5	0.8	1.6	5.6

C_{carb}, carbonate; C_{org}, organic carbon.

*The survey station was located at longitude 81°53'W and latitude 5°21'N.

TABLE 5.

OPAL, ORGANIC CARBON, NITROGEN, AS PERCENTAGE OF TOTAL SEDIMENT FLUX AT THE PANAMA BASIN SURVEY STATION.
After Honjo et al., 1982.

Station and depth, m	Constituents		
	Opal %	Organic carbon %	Organic nitrogen %
Panama Basin			
PB 667	22.51	11.0	1.3
1,268	21.74	8.6	1.1
2,265	20.42	7.2	1.0
2,869	19.58	6.9	0.9
3.769	16.42	5.2	0.7
3,791	16.40	5.9	0.6
Sediment	6.6	1.7	0.2

The data presented in Tables 4 and 5 indicate drastic change in contents of the constituents in the water column (mass flux) and bottom surface (top layer) sediments. The low concentration of opal is most likely caused by the solution of the sediment under the conditions of opal undersaturation in oceanic water. The sudden change of the organic carbon has not been fully explained. It is believed, however, that sinking material is significantly altered by the biochemical processes at a depth of approximately 200 m above the ocean bottom at the survey station (Deuser and Ross, 1980).

Generalized lithology and stratigraphic sequence of the sedimentary cover in the Panama Basin is shown in Figure 16. It appears that the oldest sediments detected are of middle Miocene age (DSDP Sites 155 and 158). This age is in agreement with increasing age of the basement outward from the rifting zone.

The lithostratigraphic profiles from the Panama Basin well illustrate a significant degree of the depositional uniformity throughout most parts of the region. This uniformity refers mainly to the hemipelagic type of prevailing sediments. In the sedimentological sequences, the upper sections usually consist of nannofossil chalk oozes rich in calcareous and silicaceous microfossils. Chalk oozes overlay gradually indurated chalk sequences with some chert stringers and nodules which represent postsedimentary diagenetic processes.

Rates of sedimentation show significant differences which resulted from the combination of biological production, topography of the oceanic floor, eustatic changes of sea level, intensity of the upwelling oceanic currents and others (Figure 17).

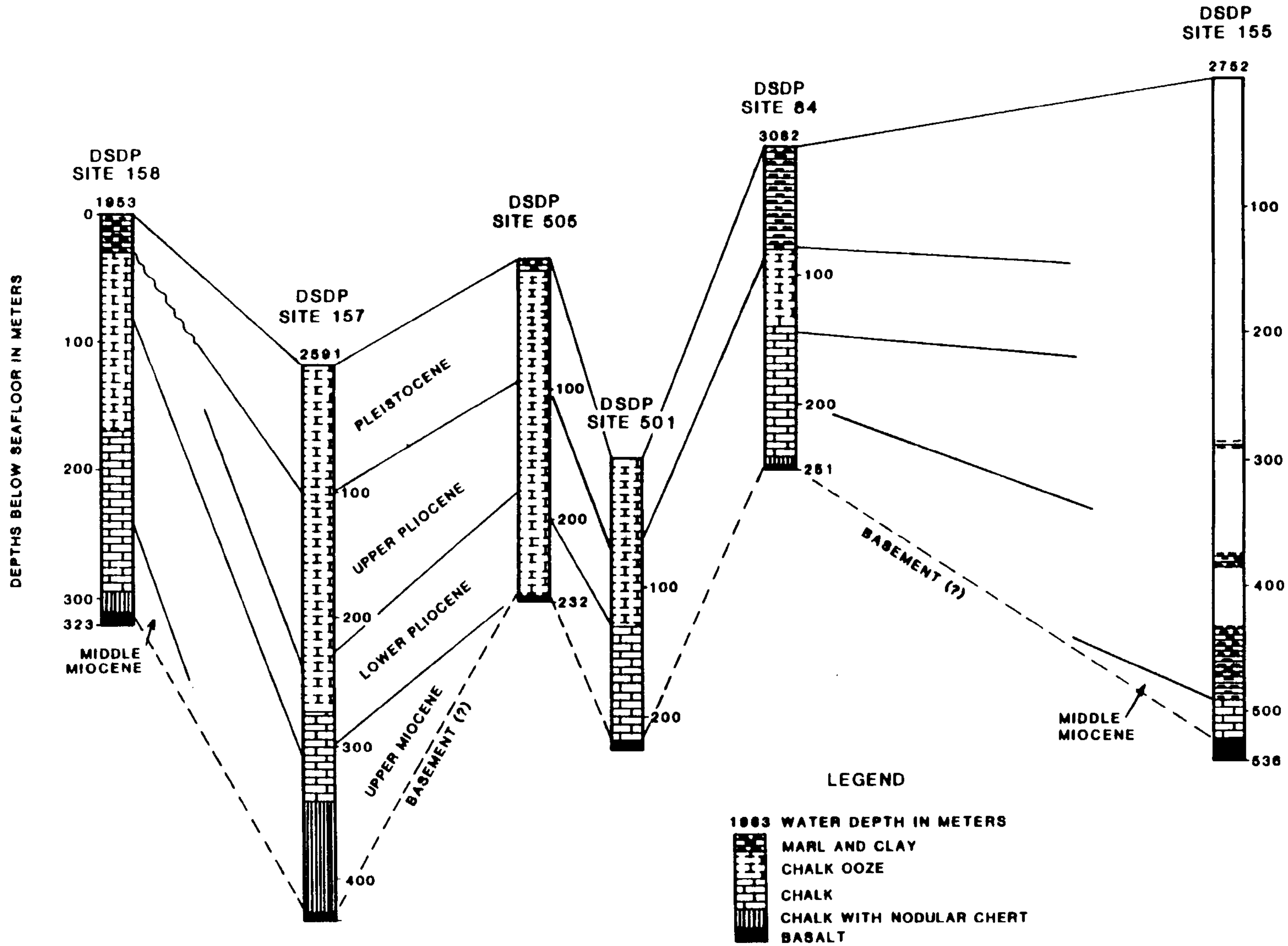


Figure 16. GENERALIZED LITHOLOGY AND STRATIGRAPHY OF THE PANAMA BASIN (BASED ON DSDP BOREHOLES)

Modified after Heath and van Andel, 1971

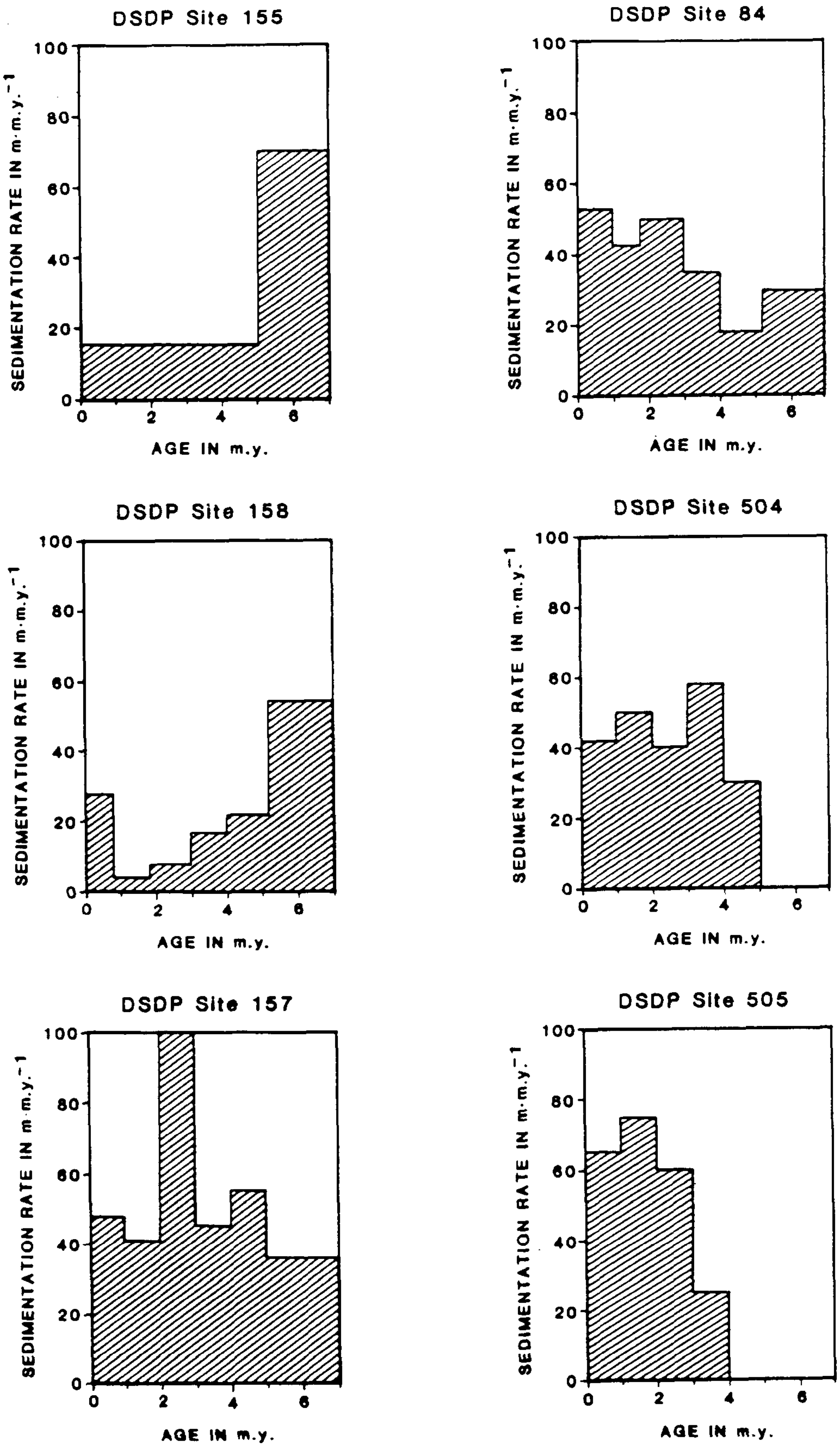


Figure 17. RATES OF SEDIMENTATION IN THE PANAMA BASIN
Based on DSDP data

The northern and easternmost parts of the Panama Basin are probably more diversified lithologically. At DSDP Sites 84 and 155, the proximity of the land in Pliocene and Pleistocene sediments is reflected by the presence of marly and clayey sediments. Also, increased presence of volcanic ash seems to be related to the proximity to the volcanically active regions (Terry, 1956). The depositional sequences in the northern and eastern margin of the Panama Basin can merely be the subjects of speculation as there are no rock samples recovered from the margin. Case and Holcombe (1980) marked two drilling locations in the Gulf of Panama which are presumably the sole wells in the northernmost part of the Panama Basin. The lithostratigrahic profiles of these latter wells are property of an unspecified oil company (personal communication, T. Holcombe). The event of closing water communication between the Pacific and Atlantic Oceans 3 to 5 m.y. ago must have been reflected in the lithology of the northern margin of the Panama Basin by an increase in terrigenous and paralic facies and volcanogenic material. Lowrie (1978), who advocates the presence of a buried subduction zone in the northern margin of the basin, seismically derived the thickness of the sediment cover in the area. According to Lowrie's calculation, the sedimentary cover in the northern margin of the Panama Basin amounts to approximately 2,000 m.

The depositional history of the eastern continental margin of the Panama Basin is obscure. A number of tectonic events superimposed on each other resulted in a very complex present picture of the area. The eastern margin of the Panama Basin is generally considered as a trench and near trench environment (Pennington, 1981). Thicker sedimentary cover can be expected in this area. However, the system of grabens separates the marginal, relatively narrow areas of the basin from the inner Panama Basin northward and is covered with thin sediments.

Lithostratigraphic Profiles of Deep Sea Drilling Project Sites

Deep Sea Drilling Project (DSDP) sites (Figure 1) have provided first and up to the present time the only information on the lithostratigraphy of sediments in the Panama Basin. The choice of the DSDP sites was originally dictated by need of checking and verifying the concepts on tectonic development of the basin. The elevated ridges have been of particular interest as the understanding of their origin should elucidate the evolution of the region. Brief characteristics of the DSDP sites are presented in Table 6.

TABLE 6.

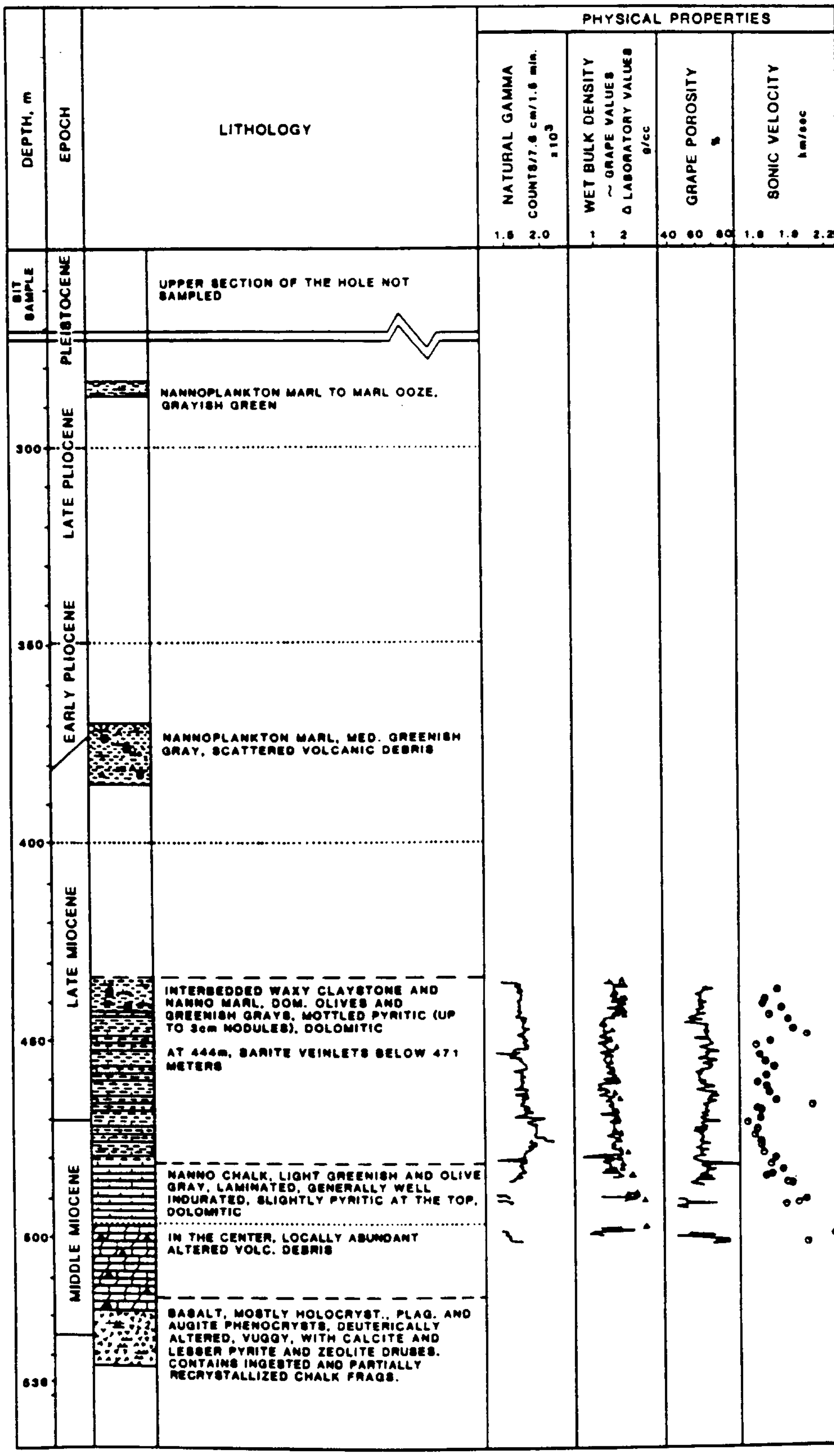
SUMMARY DATA FROM DEEP SEA DRILLING PROJECT SITES IN THE PANAMA BASIN

DSDP site	Location	Geologic unit	Ocean depth, m	Thickness of sediment, m	Age of the oldest sediment,	Acoustic velocity in sedimentary column, m/s
84	05°44.92'N 82°53.29'W	Abyssal zone	3097	255	Upper Miocene	1340
155	06°07.38'N 81°02.62'W	East slope of Coiba Ridge	2752	536	Middle Miocene	1650
156	01°40.80'N 85°24.06'W	Carnegie Ridge	2369	4	Quaternary	-
157	05°44.92'N 82°53.29'W	Carnegie Ridge	1591	437	Late Miocene	1530
158	06°37.36'N 85°14.16'W	Cocos Ridge	1953	323	Middle Miocene	1649
504	01°13.58N 83°43.93'W	Abyssal zone	3460	275	Late Miocene	-
505	01°54.82'N 83°47.39'W	Abyssal zone	3547	242	Late Miocene	-

Site 155. In the profile of DSDP Site 155 (Figure 18) four basic types of sediment were found (van Andel et al., 1973): mottled nannofossil marl, waxy claystone, mottled marly clay, and marl with nannofossil foraminiferal chalk. Although three first lithotopes are interbedded, they form four distinctive lithostratigraphic units in the vertical profile:

Unit 1 is represented by an intensely mottled olive and light olive nannofossil marl with lighter, more calcareous mottles or with darker mottles rich in finely disseminated pyrite. In most beds of this unit the pyrite-bearing layers are up to few centimeters in thickness. Also pyrite nodules 0.5 - 1.0 cm in diameter were found. The maximum subbottom depth at which the sediments typical for this unit were encountered, was 454.3 meters.

Unit 2 features mostly homogeneous, massive and possibly bentonitic claystone. The predominant color of the unit is medium greenish-gray and darkens with depth. Recovered cores showed the undisturbed 2 - 6 cm thick claystone layers, interbedded with 1 - 3 cm thick sequence of thoroughly disturbed material. Beds of Unit 2 are occasionally interbedded with lithotopes mostly characteristic for Unit 1. Such alternation occurs between



LAT. 06°07', LONG. 81°02.62' W; WATER DEPTH 2752m

Figure 18. LITHOSTRATIGRAPHY AND PHYSICAL PROPERTIES OF SEDIMENTS AT DSDP LEG 16, SITE 155, PANAMA BASIN, COIBA RIDGE

After van Andel et al., 1973

441 - 466 m. Contacts between claystone and other sediments are usually marked by layers of fine pyrite and pyrite nodules, and occasionally by silt-size crystals (e.g. at 444 m below ocean's floor).

Unit 3 consists of sediments graded from marly clay to marl while the carbonate content in the unit is generally diminished in comparison with Unit 1. The colors of the sediments of Unit 3 vary from various shades of olive to green and gray. Pyrite nodules and pyrite-rich claystone layers several millimeters to several centimeters thick occur quite frequently. The lithological associations of Unit 3 were found at the interval 456 to 484 meters below the ocean's floor.

Unit 4 underlies Unit 3 and is represented by chalk sediments. The color of the chalk grades from light green at the top to very light gray downward. At 490 m depth, the rocks become dolomitic, massive, and well indurated. The interval between 490 - 519 m (below the ocean floor) shows softer material, mainly yellowish to olive gray chalk-marl. There is an increased amount of medium to coarse-grained sand which reaches 5% at near 500 m. Individual grains of sand are clayey aggregates probably derived from decomposed fragments of the crustal basalts and basaltic glass. The contact between Unit 4 and basaltic basement occurs a depth of 519 m below the oceanic floor.

The bottom section of 100 meters of drill hole at Site 155 was continuously cored. Foraminifera, coccoliths and radiolarians constituted the base on which the age of middle and upper Miocene of the cored sediments was established. Three sidewall cores from the upper sections of the hole (285, 371, and 384 m) were recovered. The sediments of these sections were dated as Pliocene age.

Biostratigraphic analysis and analogy with other DSDP sites in the Panama Basin made it possible to conclude that a thick Tertiary sequence is probably present in vertical profile of the DSDP Site 155 (Figure 18).

Site 158. The sedimentary sequence at Site 158 (Figure 19) consists of chalk oozes grading downward into chalks with basal chert beds (van Andel et al., 1973). Basalt basement was encountered 322 meters below the oceanic floor. Three lithologic units can be distinguished in the profile of DSDP Site 158:

Unit 1. Nannofossil chalk ooze with three subtypes (measured downward from oceanic floor):

a. 0 - 30 m. This interval consists of foraminiferal, ashy marly nannofossil ooze with common radiolaria. At the depth of 2 m, a 10 cm thick layer of white volcanic glass was found. Also silt-sized volcanic glass with pyrite occurs in an olive-black bed 5 cm thick at 15 m and in a 2 cm thick light olive layer at 20 meters. Ashy laminations several millimeters thick are scattered throughout this unit. Prevalent colors are dusky yellow green and pale to grayish olive. Mottling in this interval is slight to moderate and the sediment is locally enriched in pyrite. On fresh surfaces the sediment had a faint H_2S odor.

b. 30 - 70 m. The sediments consist of foraminiferal nannofossil ooze, virtually free of quartz and feldspar. Only small amounts

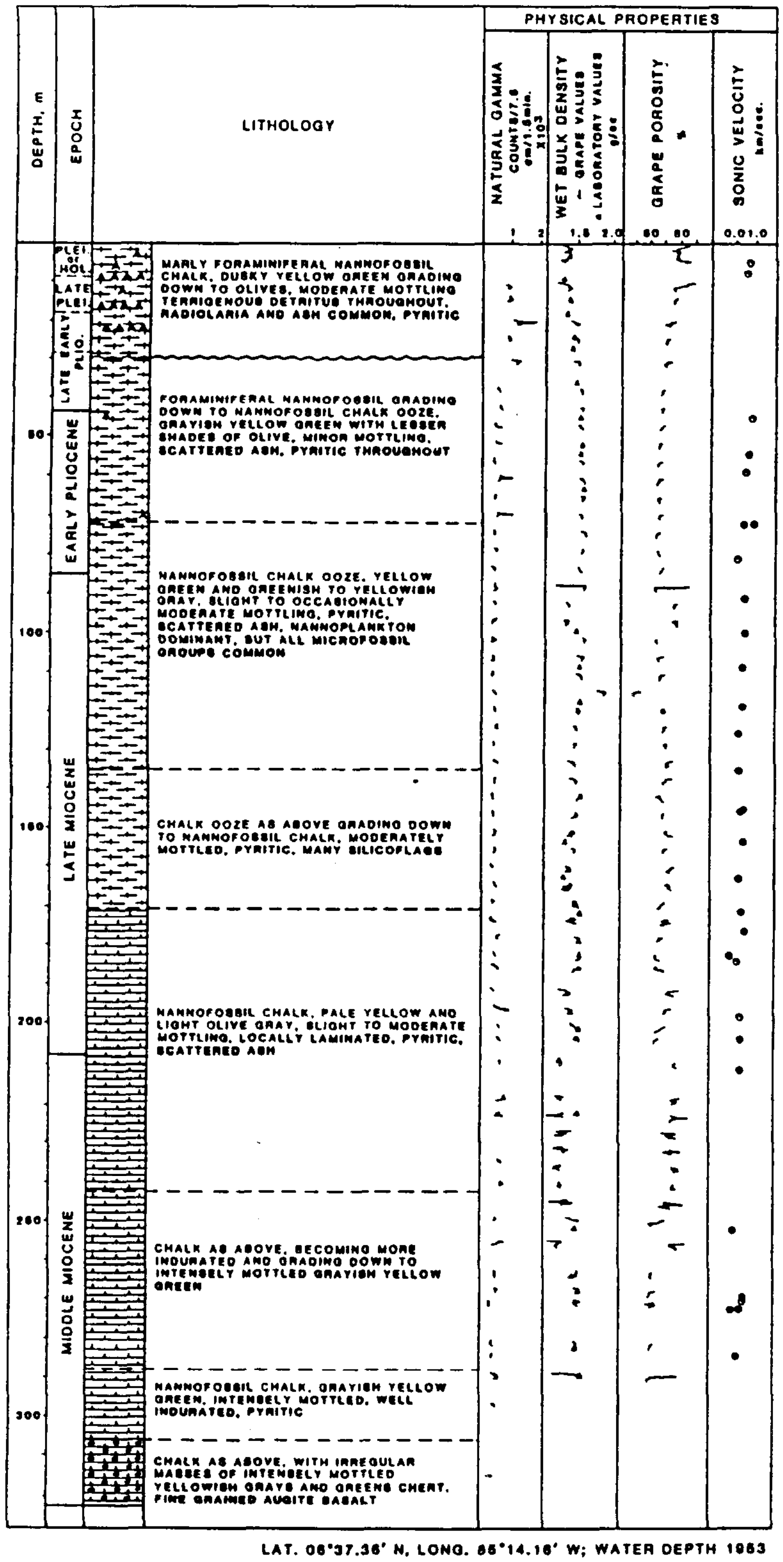


Figure 19. LITHOSTRATIGRAPHY AND PHYSICAL BACKGROUND OF SEDIMENTS AT DSDP LEG 16 SITE 158, PANAMA BASIN, COCOS RIDGE

of light and dark glass were found. Silt-sized pyrite granules are ubiquitous in small amounts. The abundance of foraminifers was found and radiolarians are common in this interval. Diatoms, while absent in the top one-third of the interval, and appear in small amounts below. Mottling has not been observed. A faint H_2S odor was noticed.

c. 72 - 135 m. The interval represents a nannofossil chalk ooze with small amounts of silt-sized feldspar. The amount of volcanic glass slightly increases compared with the overlying section. Silt-sized pyrite is scattered throughout the section in small amounts. The trend of downward decreasing abundance of foraminifers was found to be accompanied with an increase in diatoms which are abundant near the bottom of the interval. Variations in the content of radiolaria show a maximum in the middle of the unit. Mottling increases and becomes dominant in the lower section of the unit where burrows up to 1 cm wide and 4 to 6 cm long can be observed. H_2S odor was noticed only in the upper part of the unit.

Unit 2. The second unit (135 - 305 m) comprises a transitional zone between nannofossil ooze and nannofossil chalk and a zone of well indurated chalk.

Unit 3. This unit, extending from 305 to 322 meters below the ocean floor, consists mainly of nannofossil chalk with interbedded chert, which occurs immediately above the basaltic basement. The thick strata of interbedded chert and chalk (i.e. 12 to 20 cm thick layers of chalk interbedded with 1 to 5 cm of chert) were recovered from the interval of Unit 3. The chalk rocks in Unit 3 are identical to those in the overlying beds of Unit 2 except for a greater abundance of feldspar, palagonite and glauconite, and almost complete absence of the volcanic glass. There is no microscopic evidence for recrystallization of the carbonate even close to the basalt.

Chert occurs in two forms and can be found in contact with both grayish-yellow chalks and with olive-gray limestone. The contact with chalks is very sharp and the chert is composed mainly of microcrystalline cristobalite. The chert contains 10 to 15 percent calcite. Silicification has been more developed in the olive-black cherts in contact with the limestone. The cherts occuring on contact with olive-gray limestone are composed almost entirely of 10 to 20 grains of chalcedonic quartz. The contact between the chalcedonic cherts and limestone shows a zone of isotropic cristobalite. Both the limestone and the chert contain small amounts of fine disseminated pyrite. The top of the basaltic basement was found at a depth of 322 meters below the oceanic floor.

The analysis of foraminifera, coccoliths and radiolarians brought the evidence for the presence of a nearly complete sequence of middle Miocene to Pleistocene age sediments at Site 158.

Site 157. The sediments in the profile of DSDP Site 157 (Figure 20; van Andel et al., 1973) display significant lithological uniformity. The sedimentary sequence is 431 m thick and consists of nannofossil chalk ooze and chalk

FIGURE 20, Lithostratigraphy and Physical Properties of Sediments at DSDP Leg 16 Site 157, Panama Basin, Carnegie Ridge, is located in the pocket at the end of the report.

which become increasingly indurated with depth. The upper part of the section above 342 m is rich in biogenic silica from radiolarians and diatoms. Below 342 m all silica is in the form of chert stringers and nodules indicating a much lower degree of preservation of the siliceous organisms. Foraminifers are present in abundance in the near surface sediments. However, the amount of foraminifers decreases below 50 meters from the top of the sedimentary sequence. Foraminifers remain common to abundant to the depth of 250 m and are common to 342 m. The dominant components are nannofossils followed by diatoms, the abundance of which decreases markedly below 333 m. Radiolarians are common throughout the section to 324 m, and they disappear below 345 m.

The boundary between chalk ooze and chalk has been inferred arbitrarily at 285 m, based on the rate of drilling (i.e. ooze is much softer because it cosists of loose sediment). The shallowest occurrence of chert was encountered at depth of 342 meters. Below this depth cherts are alternated with nannofossil chalk and chalk limestone. Mottles and burrows are common in this section. Fine-grained pyrite occurs frequently in the form of darker grey laminae and streaks and greyish to black concentrations. The chert is mostly calcareous and usually it is darker than the associated chalk and chalk limestone.

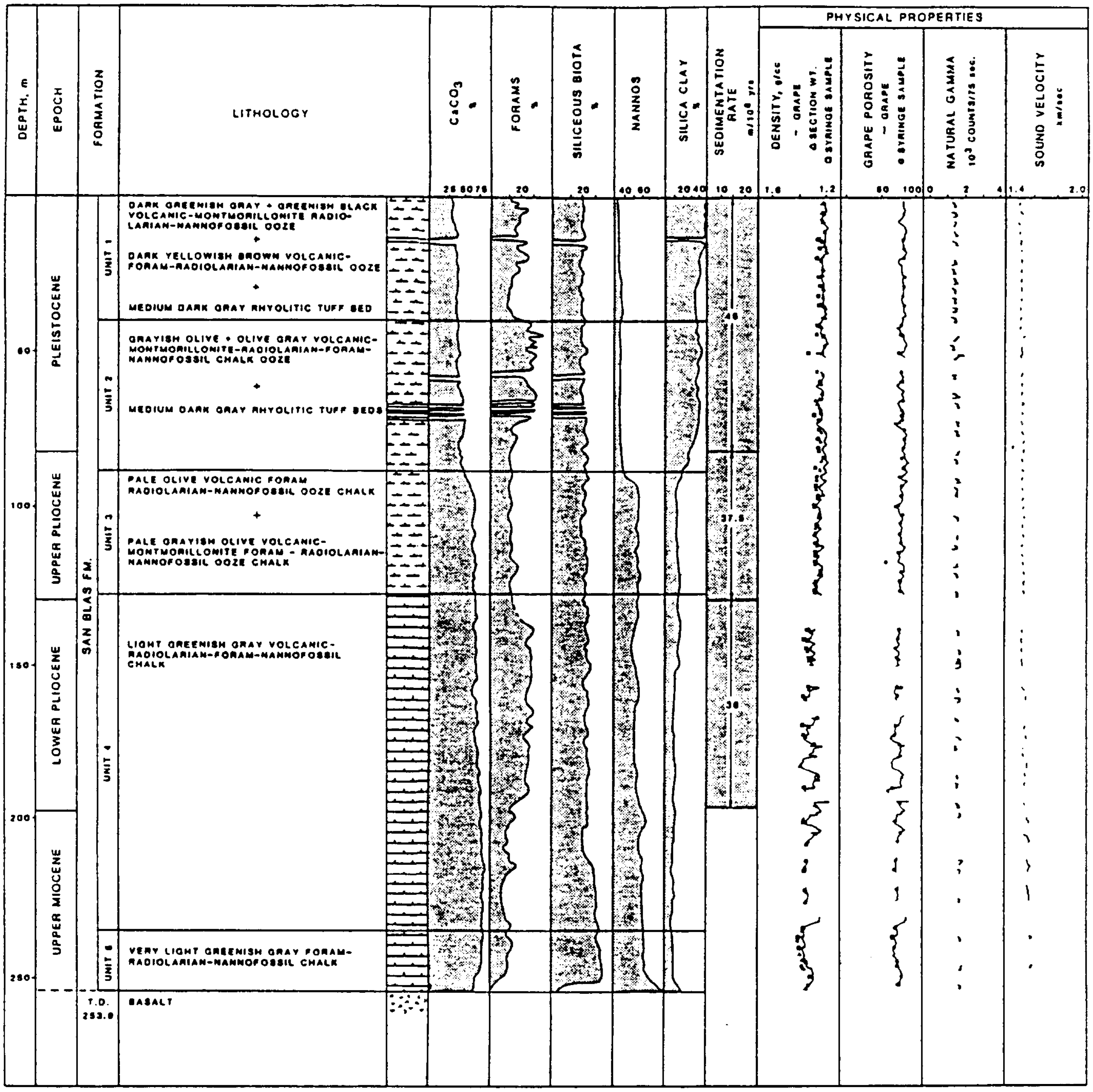
The paleontological investigation of the material recovered at Site 157 indicates that the sediment immediately above the basaltic basement is of late Miocene age. It appears that the complete sedimentary sequence from the upper Miocene to the upper Pleistocene is present in vertical profile of Site 157. The final assessment as to whether the uppermost Pleistocene sedimentary column is missing has not been made.

Site 156. Only 49 cm of the top of the sedimentary sequence was recovered at this site due to the technical difficulties (van Andel et al., 1973). The upper 34 cm of the core consisted of a calcareous sand intensely disturbed by coring. This unit of Quaternary age was abundant in planktonic foraminifers, radiolarians and nannofossils. Underneath, hard ferromanganese-oxide crust was encountered.

Site 84. The lithology of the sedimentary sequence reflects the proximity of Site 84 to the land (Figure 21; Hays et al., 1972). The upper 81 m (Pleistocene) contain numerous ash layers and other continentally derived material. There are no ash layers below the Pleistocene sequence. The volcanic glass occurs, however, throughout the section and diminishes downward. Sedimentary cover at DSDP Site 84 is 253.9 m thick, referred to as the San Blas Oceanic Formation (Hays et al., 1972). At DSDP Site 84, the San Blas Oceanic Formation has been divided into five units based on different shades of green color and burrowing. The green coloration is derived from large amounts of green montmorillonite which is the alteration product of pyroclastic materials.

Five lithologic units can be distinguished in the profile of DSDP Site 84:

Unit 1 (0 - 39.6 m) represents the darkest green unit and consists of dark greenish-gray montmorillonite, radiolarian foraminiferal and calcareous nannofossil ooze, volcanics and montmorillonite chalk.



05°44.92' N, 82°53.29' W; 3097m WATER DEPTH

Figure 21. LITHOSTRATIGRAPHY AND PHYSICAL PROPERTIES OF SEDIMENTS AT DSDP LEG 9 SITE 84, PANAMA BASIN, ABYSSAL PLAIN

After Hays et al., 1972

Unit 2 (39.6 - 87.4 m) has lighter coloration than Unit 1. Beds 1 to 75 cm thick are slightly burrowed in the basal 15 m. In addition to montmorillonite and radiolarian, foraminiferal and calcareous nannofossil chalk ooze there are volcanic constituents. Four rhyolitic vitric ash beds about 1 centimeter thick were detected in Unit 2.

Unit 3 (87.4 - 128 m) is lighter green than the two overlying units. The sediments form 1 to 15 cm thick beds which consist of montmorillonite, foraminiferal, radiolarian and nannofossil oozes. Volcanics constitute up to 20 percent of the sediment mass.

Unit 4 (128 - 234.6 m) is intensely burrowed while the volume of the volcanic constituents markedly decreases. The major lithotype in this unit is calcareous nannofossil chalk (50 to 60 percent) and foraminiferal chalk (20 to 30 percent).

Unit 5 (234.6 - 253.9 m) is represented by intensely burrowed light greenish-gray and yellowish-gray sediments. Radiolarian and calcareous nannofossil chalk is the prevalent type of the sediment in this unit. Within the basal 3 of the sedimentary sequence, a green calcareous nannofossil chalk has been replaced by chert. The contact between Unit 5 and underlying basalt is being interpreted as an intrusive, based on the observation of thermally altered green calcareous nannofossil chalk sediments.

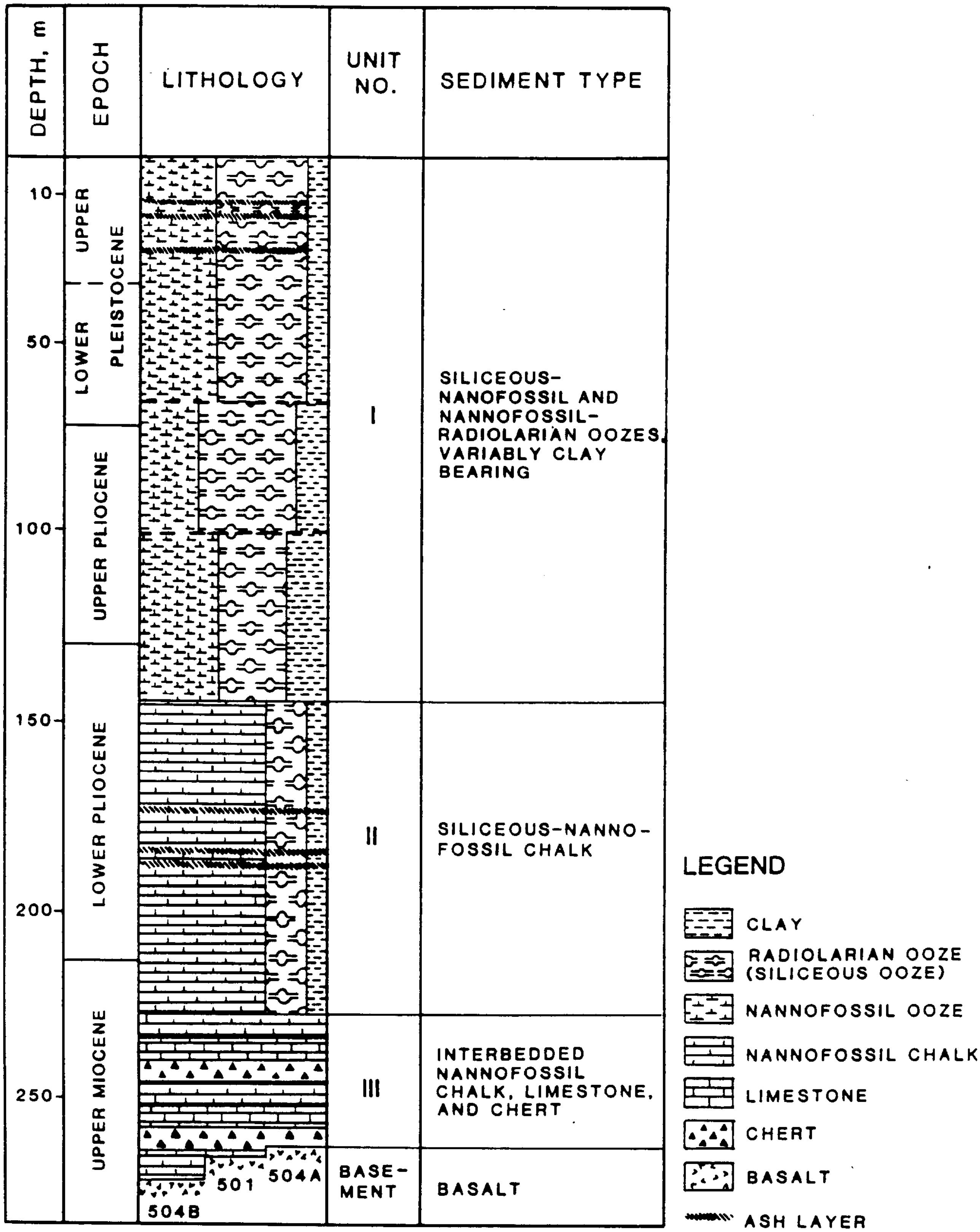
The sedimentary sequence at Site 84 was almost entirely cored. Abundance of diverse foraminiferal faunas throughout the hole made it possible to find the age of various sediments. The analysis performed indicates that the drilled column includes a complete sequence of sediments from upper Miocene to Pleistocene.

Sites 501 and 504 (Figure 22; Cann et al., 1982). In the areas of DSDP Sites 501 and 504, the sedimentary cover is 262 to 271 m thick. The lithological profiles at Sites 501 and 504 were found to be essentially the same. Therefore a summary lithological profile will be presented for both locations.

The sedimentary sequence at Site 504 consists of three lithologic units:

Unit 1 (0 - 143.5 m) with sediments of late Pleistocene to late Pliocene. Major constituents of this unit are siliceous-nannofossil and nannofossil radiolarian oozes with variable clay amounts. Three volcanic ash layers were encountered in the upper section of the lithostratigraphic column (Figure 22). Increased amounts of volcanic glass were found at both ends of Unit 1 in the intervals extending to 65 m. The firmness of the sediments at the base of Unit 1 increases considerably, leading abruptly into chalk.

Unit 2 (143.5 to 227.2 m) represents sediments of late Pliocene to late Miocene age. The sediments in this unit are mainly siliceous-nannofossil. Volcanic glass occurs in trace amounts except for three thin ash layers at depths of 173 m, 183.4 m and 187.3 m. From 168.4 m downward, the corrosion of foraminifers became significant. Also enhanced calcitic overgrowth of discoasters indicates an increased diagenetic calcite dissolution and reprecipitation.



SITE 501 - LAT. 01°13.63' N, LONG. 83°44.06' W, WATER DEPTH 3457m;
SITE 504 - LAT. 01° 13.58' N, LONG. 83°43.93' W, WATER DEPTH 3458m

Figure 22. SUMMARY PROFILE OF LITHOSTRATIGRAPHY AT DSDP LEGS 68, 69, SITES 501 AND 504

After Cann et al., 1982

Unit 3 (227.2 - 271 m) embraces the sediments of late Miocene. The sediments consist of interbedded nannofossil chalk, limestone and chert. All rock types show strong vertical compaction which resulted in fine horizontal lamination. Although the compaction measured on zoophycos burrows was approximately 80%, numerous open foraminifer chambers occur in the chalk as well as in the limestones. With increasing depth the increased "tendency" toward chertification has been observed. Chert beds never seem to exceed a few centimeters in thickness. They occur in the form of layers or stringers a few centimeters thick. Irregular chertified portions within the limestone and nodular cherts also occur in Unit 3.

The datums of sediment at Sites 501 and 504 are generally less reliable due to the rarity of marker species in some intervals and poor preservation resulting from diagenesis or carbonate dissolution. Nevertheless the Pliocene/Pleistocene and Miocene/Pliocene boundaries could be tentatively defined (Figure 22). The oldest sediments are of late Miocene age and are followed by sedimentary sequences of Pliocene and Pleistocene.

Lithostratigraphy in eastern Panama (eastern Panama Isthmus). In the absence of drilling data from marginal areas of the Panama Basin the only reference to the lithostratigraphic sequences is available from the onshore of eastern Panama. The summary lithostratigraphic profile from eastern Panama is shown in Figure 23 (Bandy and Casey, 1973). The base of sedimentary sequence consists mainly of deformed cherts and thin-bedded siliceous radiolarian-rich abyssal oceanic rocks. Two abyssal volcanic phases are marked in the sedimentary cover and they are represented by tuffaceous sediments. One volcanic phase of early to middle Eocene was found in the lower and middle section of the Morti Tuffs Formation (Figure 23). The second volcanic phase occurred in the middle Oligocene and lower Miocene. Also, two erosional events have been documented in the sedimentary sequence of eastern Panama (Bandy and Casey, 1973). One hiatus separates deep-water Late Cretaceous sediments from deep-water facies of middle Oligocene to lower Miocene. The second major hiatus followed deep-water deposition of the Morti Tuffs Formation. The second erosional event took place during late Eocene to early Oligocene. Since late Oligocene the sedimentary sequence indicates shallower deposition environment resulting from the beginning of the final uplifting process of the Panama Isthmus.

Geothermal Characteristics

Generally, the Panama Basin represents the region with high values of heat flow which in some areas exceed 200 mW/m^2 (Bowin, 1976). The map of the heat flow distribution in the basin shown in Figure 24 is modified from van Andel et al. (1971). However, it appears from this map that the heat flow pattern is not quite conformable with structural features of the region. The only area of heat flow pattern which fits well in the structural model of the basin is the one located along the Galapagos Rift Zone. The remaining parts of the Panama Basin display anomalies in the heat flow which in some instances run across structural units. One such anomaly occurs in the

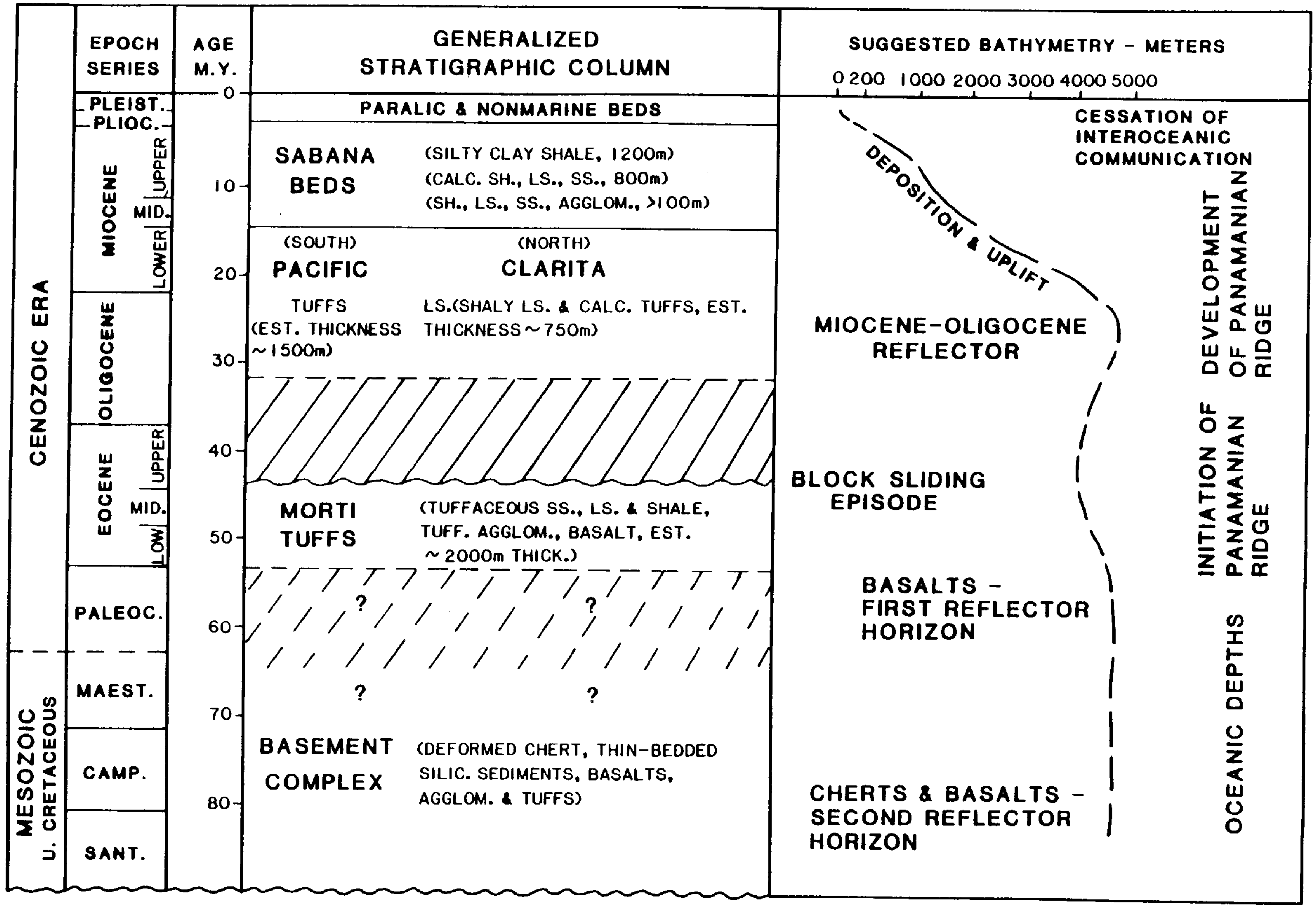
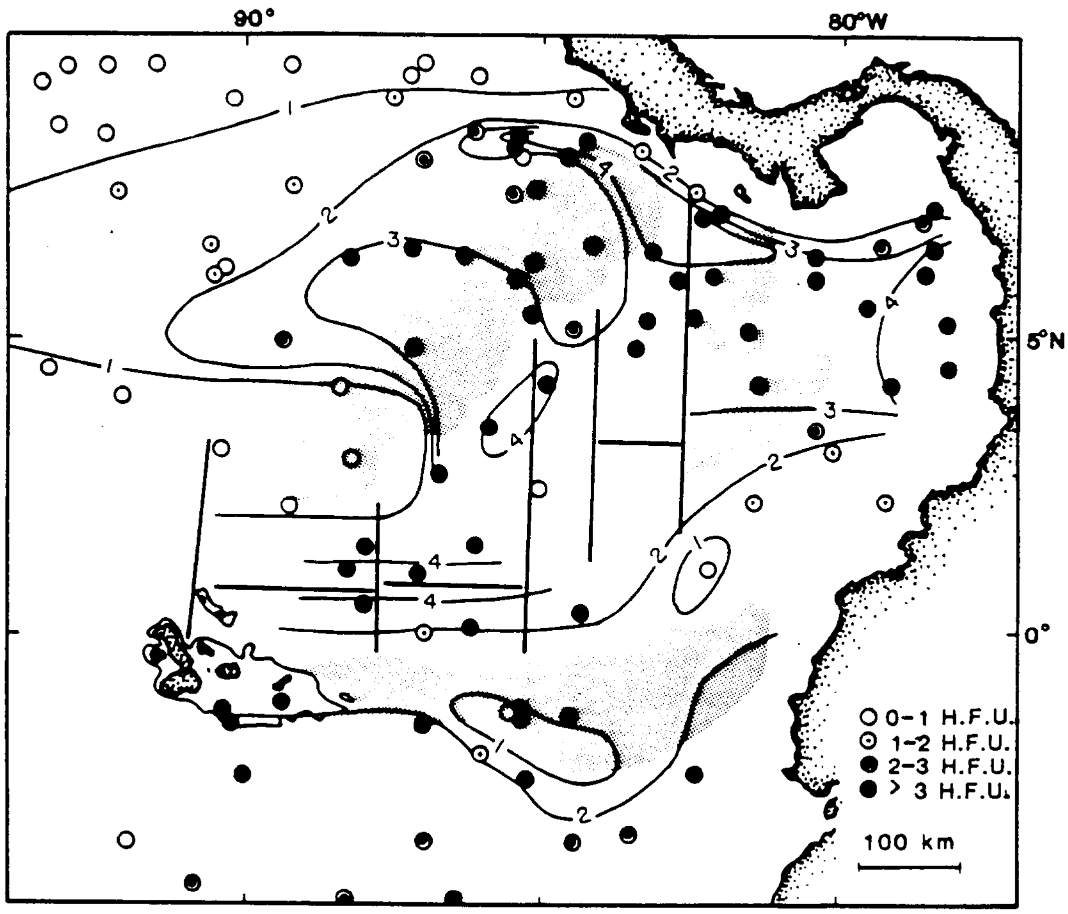


Figure 23. DEPOSITIONAL - TECTONIC FRAMEWORK OF EASTERN PANAMA

After Bandy, 1970



HEAT VALUES ARE IN HEAT FLOW UNITS (H.F.U.)

PATTERNED AREAS REPRESENT ELEVATED PARTS OF THE BASIN (RIDGES)

Figure 24. HEAT FLOW IN THE PANAMA BASIN

After van Andel et al., 1971

northwestern part of the Panama Basin. The explanation of the irregular heat flow distribution lies most likely in the pattern of sedimentation and erosion.

Most of the studies on geothermal conditions of the Panama Basin have been focused in the vicinity of the spreading rifts (e.g. Lonsdale and Klitgord, 1978; Corliss, 1979). However, the rifts do not represent potential for gas hydrates. Nevertheless, overall the geothermal processes may be instructive in understanding the heat flow pattern in other parts of the Panama Basin.

Interesting results have been obtained from the DSDP investigation of the geothermal processes south of the Costa Rica Rift, between DSDP Sites 505 and 501/504 (Cann et al., 1982; Figure 25). The two groups of DSDP sites are about 76 km apart and display diametrically different geothermal regimes. The age of crust at Sites 505 and 504 is 3.9 m.y. and 5.9 m.y. with an overlying sedimentary sequence of a comparable thickness (242 m and 270 m respectively). The temperatures at the contacts between basement crust and sediment were found to be about 9°C at DSDP Site 505 and about 60°C at Site 504 (Figure 26). These two temperatures correspond respectively to the heat flow of 29 mW/m^2 and 200 mW/m^2. In the areas of DSDP Sites 501 and 504, the average observed thermal gradient amounts to 0.267 ± 0.026°C/m. On the other hand, the lowest thermal gradients in the sedimentary cover of 0.016°C/m were observed in a broad trough in the survey area where DSDP Site 505 is located (Langseth et al., 1980). The two locations display remarkable differences in terms of the crust relief. The northern area (DSDP Site 505) has very a pronounced relief where the major topographic elements are an 80 km long ridge and a 15 km wide trough south of the ridge. Both forms stretch in west-east directions. Significant roughness of the area is expressed by fault blocks with offsets of 100 to 200 meters. The numerous outcrops of the basement enable seawater to circulate freely at the upper crust. As a result of this, the process of thermal advection takes place, maintaining relatively low temperature in the upper crust. Lister (1972) and Hyndman et al. (1977) noted the described phenomenon along young oceanic ridges (including mid Atlantic and Pacific Ocean ridges).

The southern area (DSDP Sites 501/504) is characterized by a sedimentary cover about 270 m thick overlying relatively smooth basement. The relief of the basement in this area is associated with small escarpments which reflect faults with offsets less than 100 meters. Anderson and Hobart (1976) determined that in the area about 200 km south of the Costa Rica Rift, the sedimentary cover of about 250 m is capable of preventing almost all heat exchange between the oceanic water and underlying crust. Subsequently it was found that heat conductivity is the major process of the heat flow in the sedimentary cover. Generally the studies of the geothermal conditions in DSDP Sites 505 and 501/504 show that the low thermal gradients are associated with low values of heat flow and conversely the high thermal gradients are found in the areas with high heat flow.

The areas of the continental margin within the Panama Basin are the least documented with regard to the geothermal gradients. Analysis of the seismic bottom simulating reflectors (BSRs; Figures 32 - 36) and experimental data on temperature and pressure of hydrate dissociation (Kuuskraa et al., 1983) made it possible to estimate the geothermal values in sedimentary sequences of these areas. The values of 0.04° to 0.05°C per meter in the upper sedimentary intervals are in agreement with the depths of gas hydrate zone presented by Shipley et al. (1979).

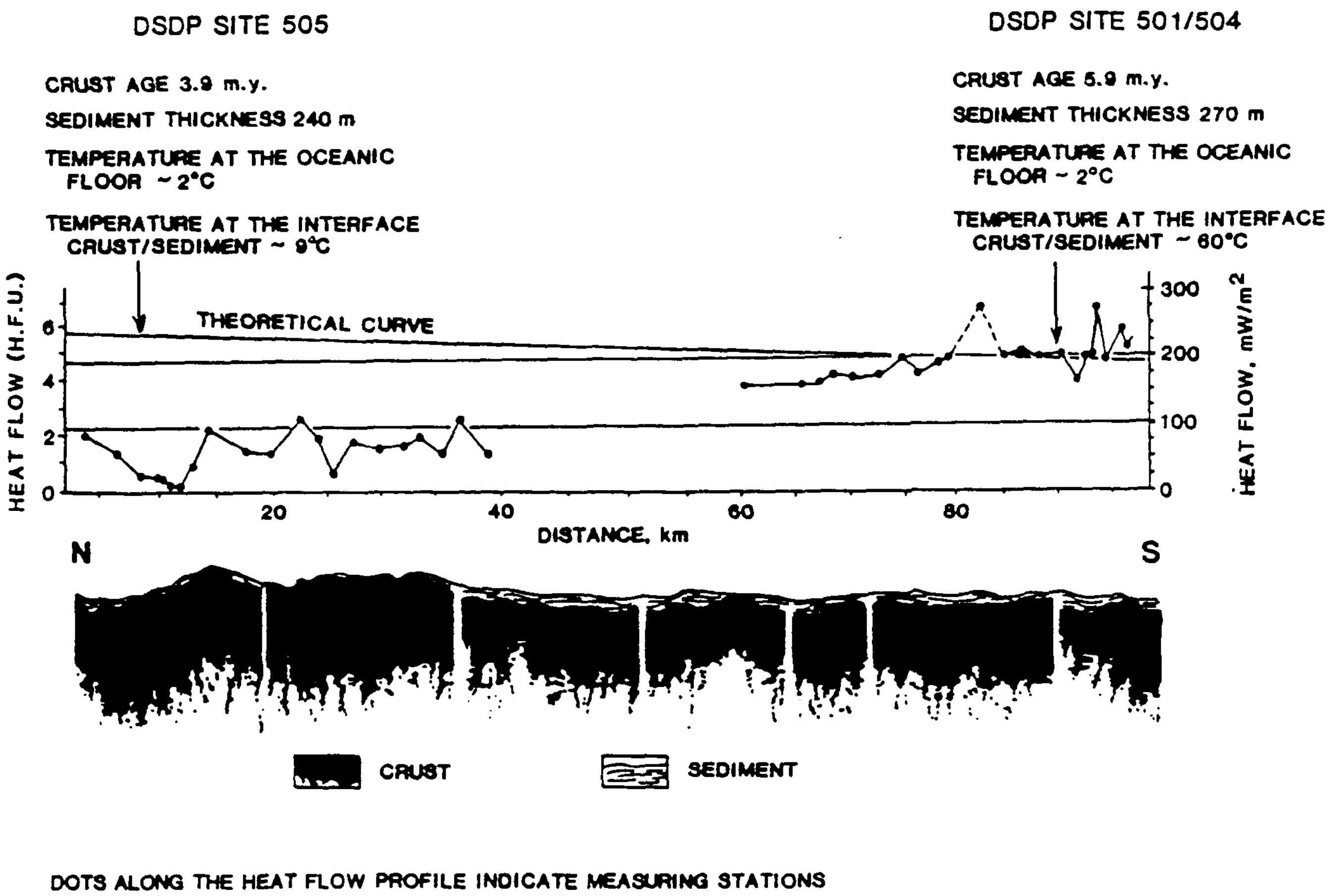


Figure 25. HEAT FLOW PROFILE ALONG THE TRACK BETWEEN DSDP SITES 505 AND 501/504, WITH SIMILARLY SCALED SINGLE CHANNEL SEISMIC RECORD SHOWING BASEMENT TOPOGRAPHY AND SEDIMENT THICKNESS

Modified after Cann et al., 1982

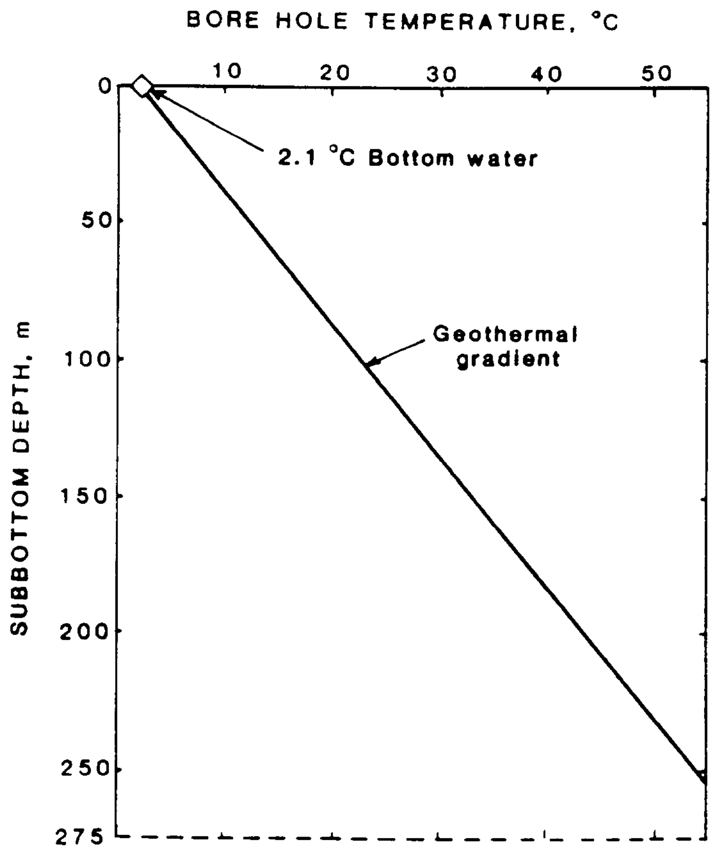


Figure 26. GEOTHERMAL GRADIENT AT DSDP SITE 504 B

After Becker et al., 1982

Considering the limited amount of available data on the geothermal regimes in the Panama Basin, the following conclusions can be made:

Generally the Panama Basin region is geomorphologically rugged. The suboceanic basement outcrops are common. Numerous fault offsets exceed 100 m. In most of the region, with the exception of the northern and eastern continental margins, the sedimentary cover is thin. In such conditions geothermal gradients are generally low, probably similar to the measured values at DSDP Site 505 (0.016°C/m). However, the geothermal gradient measured at DSDP Sites 501/504 shows much higher values (0.267°C/m). Moreover, within the northern and eastern continental margins, the thickness of the sedimentary cover exceeds 2,000 m. In these margins the geothermal gradient ranges from 0.04 to 0.05°C/m.

Discussion

The structural and paleogeographic developments of sedimentary basins as discussed in Part I of this report have important bearings on the gas hydrate formation and stability conditions. The structural phenomena define sedimentological regimes which may produce favorable environments for the gas hydrate host strata. Directly related to the strŭctural development of a sedimentary basin are the following factors:

1. bathymetry,
2. geomorphology of the basement (oceanic crust),
3. regional and local structural setting (tectonics),
4. thickness of the sedimentary sequence,
5. lithology,
6. rate of sedimentation
7. rate of the depositional base subsidence,
8. geothermal conditions.

In the study of gas hydrate favorability potential, the importance of all the above listed factors always has to be considered.

The Panama Basin is relatively young. Its development started in upper Miocene time. Therefore, the initially formed structural features are still very pronounced (Figure 2). The youngest oceanic crust occurs in the proximity of the Galapagos Spreading Center (rift zone) extended east-west (Figure 1). The crust is older toward the north and south from the rift zone. West of the 85°W Fracture Zone the accretion of the oceanic crust started later than in the eastern part of the Panama Basin. Consequently, at the same latitude the age of the basement is younger west of the 85° Fracture Zone. The bathymetry of the Panama Basin is greatly determined by the configuration of the basement, which in many areas outcrops in the oceanic floor. In the northern and eastern margins of the basin the oceanic crust plunges into presumed subduction zones.

Faulting systems constitute another dominant feature of the Panama Basin. Except major faulting- zones perpendicular to the Galapagos Spreading Center, faults with west-east and northeastern trends have been identified in the basin (Figure 5). Systems of troughs and grabens are present along the eastern and northeastern margin of the basin. All these structural features control to a significant degree the thickness and geothermal conditions of the sedimentary cover, and thus determine the gas hydrate environments.

The thickness of sedimentary cover in the Panama Basin varies from 0 to 600 m and occassionally it exceeds 2,000 m. The sediment thickness strongly limits the area with gas hydrate occurrence. For this latter reason the entire western part of the Panama Basin appears to be unfavorable for gas hydrate formation. In the eastern part of the basin the most steady and relatively thick sedimentary sequence is present in its northern and eastern marginal areas. The isopach map shows abrupt changes and mostly coincides with the topography of the basement (Figures 6, 10, 11, 12).

The basement configuration and thickness of the sedimentary cover are also controlling factors of the geothermal regime. Specifically, in the areas where there is no heat exchange between the crust and oceanic water through advection (e.g. DSDP Sites 501/504) and where the sedimentary sequence is relatively thin (200 - 600 m), high geothermal gradients occur. There is still insufficient data from the Panama Basin for a detailed evaluation of the geothermal regimes, but from the existing data it appears that most of the east central part of the basin represents high geothermal gradients within sedimentary cover. The significantly lower geothermal gradients can be anticipated in the areas where the thickness of sediment exceeds 1,500 m (northern and eastern margins of the Panama Basin).

The importance of lithology with regard to gas hydrates must be considered in at least three categories:

a. source for hydrocarbon generation,
b. host rock porosity and permeability, and
c. heat conductivity.

Available data pertaining to the two first categories are too scarce for their detailed regional study. It seems, however, that biogenic methane is the main source of hydrocarbons for gas hydrate formation in the Panama Basin. The preservation of the organic matter before it reaches the methanogenesis zone occurs mainly in the areas of higher rate of sedimentation (over 40 m/m.y.) where the depositional time of the organic matter through the oxidation zone of the water column is relatively short. Considering the high production and preservation of the organic matter, the continental slopes of Panama, Colombia and Ecuador seem to be the most favorable.

The sedimentary sequences in profiles of the DSDP sites (Figure 18 through 22) show fairly uniform characteristics of marine sediments. The sediment in vertical profile consists of an upper section with chalk oozes and a lower section represented by indurated chalk and limestone. Only at Sites 155 and 84 were the signs of land "proximity" detected in sediments through increased presence of volcanic ash and marly chalk. There is probably no uniform kinetic pattern of gas hydrate formation in the marine sediments. However, the most common feature for all gas hydrate bearing sediments is relatively high porosity and permeability. It can be anticipated that more permeable sediments with increased porosity (silts, sandstones, volcanic ashes) are present in the sedimentary sequence of continental margins within the Panama Basin. The lithostratigraphic profile most closely related to the latter areas is from the eastern part of the Panama Isthmus reported by Bandy and Casey (1973; Figure 23). The elevation of the Panama Isthmus is reflected clearly in the Miocene age sedimentary sequences where more sediments of shallower marine environment are present.

The type of sediment also has an important bearing on heat flow. The heat conductivity in various rocks fluctuates. Typically, with increasing sand/shale ratio, the thermal conductivity increases and subsequently the geothermal gradients in the sediment decrease. Within carbonate sequence the heat conductivity has higher values in comparison with sands (MacLeod, 1982) and lower values of the geothermal gradients should be observed. In the Panama Basin the diversified, but mostly high geothermal gradients are determined by the configuration of the oceanic crust, and the type of sediment has a relatively minor role in modifying the thermal regime in the sedimentary cover (e.g. DSDP Sites 501/504).

The basin analysis methodology used for determination of gas hydrate formation and stability appears to also be most applicable for the evaluation of gas hydrate environment potential. In the Panama Basin the amount of factual data is greatly insufficient. Nevertheless, the study of the entire basin allows us to draw preliminary conclusions that the most prospective areas for gas hydrate occurrence are the northern and eastern margins of the basin, within the continental slopes and upper rises.

PART II

FORMATION AND STABILITY OF GAS HYDRATES

The Panama Basin represents a unique region in terms of its geological history. The tectonic development of the basin still holds many open questions which are the subject of a number of studies. In the past, most of the investigations on the basin's tectonics were focused mainly on the Central Galapagos Rift Zone and on the genesis and development of the other ridges.

The designation of the Panama Basin by the DOE-METC as one of the study areas of gas hydrate formation and stability was motivated by the presence of the bottom simulating reflectors (BSRs). The BSRs from the Pacific Ocean offshore of Panama have been reported by Shipley et al. (1979). This study shows that, in addition to the presence of the BSRs, favorable potential for gas hydrates in the Panama Basin is indicated by unusually high production of organic matter within the oceanic water column, which in conjunction with the high rate of sedimentation creates relatively high potential for generation of biogenic methane. A variety of geothermal gradients and formation pressures in many areas of the Panama Basin seems to be within the boundaries of gas hydrate stability.

The DSDP sites constitute the only source of direct geological and geochemical information. There is no geological drilling data available from the potentially most favorable areas for gas hydrates at the continental margin of Panama, Colombia and Ecuador. The results from two wells drilled in the Panama Gulf (Case and Holcombe, 1981) are still held as proprietary and have not been included in this study.

The geochemical analyses of rock samples from the DSDP sites in the Panama Basin typically were limited to the carbon and carbonate content while the pore water samples usually were analyzed for pH and salinity. However, in evaluation of gas hydrate formation potential, a strong consideration should be given to the elemental and stable isotope composition of pore water and sediment. It appears that the most detailed geochemical investigation in the Panama Basin was performed at DSDP Sites 501/504 and 505 located south of the Costa Rica Rift (Figure 1). The significance of the geochemical patterns at these sites consists of the fact that despite relatively unfavorable circumstances for the biogenic methanogenesis the presence of these processes can be observed. Consequently the areas with more favorable conditions for the methanogenesis should produce more methane.

In the situation of the severe shortage of indispensable data, the evaluation of the gas hydrate potential in the Panama Basin had to be based on the examination of the major stabilizing factors.

Sedimentary Environments

Although the complex relationships between type of the sedimentological environment, formation and subsequent stabilization of the gas hydrates are still inadequately known, several sedimentological factors seem to be particularly important:

- the presence of the sedimentary sequence within the thermal and pressure field favorable for gas hydrate stability,

- the type of sediment and the sedimentary environment favorable for generation of hydrocarbon gas, gas retention, and formation of gas hydrates,

- rate of sedimentation,

- postsedimentary erosional processes.

The thickness of the sedimentary cover in the Panama Basin shows generally increased values in northern and southern directions from the Galapagos Spreading Center (see p. 17). In the central part of the Panama Basin the sedimentary cover is determined mainly by the relief of the basement and bathymetry. Within and in proximity to the ridges, the sediment cover is continuous and evenly distributed (Figure 11). Conversely in vast rugged parts of the basin, where numerous outcrops of the oceanic crust are present, there is a lack of sedimentary cover (Figure 12). Also the discontinuous pattern of the sediment coverage can be observed in the faulted and trenched areas of the eastern marginal part of the Panama Basin. The thickest sedimentary cover in the Panama Basin (approximately 2,500 m) was inferred in the areas of suggested buried Panama Trench (Lowrie, 1978). It is also probable that strata subducted in the Colombia-Ecuador trench represent a relatively thick sedimentary sequence.

The limited seismic data and lack of drilling activities in these areas makes evaluation of these sediments as gas hydrate hosts highly speculative.

The lithofacies pattern in most of the Panama Basin as well as the physical features of the sediments show a significant degree of uniformity. The biogenic type of sediment prevails in all drilled locations (Figures 18 through 22). Lithological changes in vertical profiles in the areas north of the buried Panama Trench are poorly known. Generally, more volcanic ash and terrigenous material can be expected toward northern marginal parts of the basin. Similarly, more terrigenous material can be anticipated in the sedimentary sequence of the easternmost parts of the Panama Basin.

The sedimentation in the Panama Basin, despite variations in the rate, remained fairly steady throughout the basin's evolutionary time. The erosional events had relatively limited extent and were caused mainly by water currents. There is no evidence of long distance transportation of eroded material (van Andel et al., 1973). Redeposition of the sediment usually took place in close vicinity to the locations of the original deposition. Some evidence has been gathered on the occurrences of slumping processes in the slope areas of the ridge. Also locally these processes were identified on the continental slopes along the Panama Basin margins.

The role of sediment grain size, porosity and permeability in the process of gas hydrate formation has been discussed by Makogon (1978), Krason and Ridley (1985a, 1985b) and Krason and Ciesnik (1986). Sediment of smaller grain size and lower permeability is more capable of slowing down hydrocarbon gas migration. This feature creates one of the important requirements of gas supersaturation in the process of gas hydrate formation (Makogon, 1978). On the other hand, the sediments with low permeability represent an unfavorable environment for gas diffusion necessary for the progressive growth of the hydrates once the process of their formation is initiated.

Thus, with regard to the type of sediment, the marine sediments of the Panama Basin may constitute the environment favorable for the disseminated type gas hydrates. Better conditions for gas hydrate formation probably exist in the areas of high permeability. The study of these processes requires, however, more data.

Hydrocarbon Sources

Formation of gas hydrates requires an abundance of methane and/or other hydrocarbon gases. Methane can be derived from two sources:

- bacterial degradation of the organic matter, under anoxic conditions in sediment, and

- upward migration of natural gas generated by thermal degradation of the organic matter at deeper intervals.

The two types of methane are often referred to as biogenic and thermogenic gas. Currently, two major indicators are used in establishing the origin of the gas: carbon isotopic composition of a gas and its molecular composition (Fuex, 1977; Schoell, 1983; Waples, 1981). The isotopic composition factor ^{13}C is defined as (values are reported in "permil," abbreviated "°/₀₀"):

$$\delta\ ^{13}C = \frac{(^{13}C/^{12}C)\ \text{sample}}{(^{13}C/^{12}C)\,\text{standard}} -1 \times 1{,}000$$

Biogenic methane is usually characterized by values of ^{13}C below the range of -55 to -60°/₀₀ and is associated with very low content of C_{2+} (<0.1%).

Conversely, thermogenic methane displays $\delta^{13}C$ values higher than -45 to 30°/₀₀ and is usually accompanied by 1% or more of C_{2+} hydrocarbons (Claypool and Kaplan, 1974). Attempts have also been made to relate the differences in $\delta^{13}C$ values to the type of organic matter (Parker, 1976; Gearing et al., 1977). These studies were based on the findings that terrestrial plants are enriched with $\delta^{12}C$ relative to marine plants (Wickman, 1952; Craig, 1953).

The inventory of the isotopic and geochemical data concerning hydrocarbon generation in the Panama Basin is insufficient for satisfactory assessment of the hydrocarbon generation processes. Nonetheless, the existing materials support the conclusion that in the Panama Basin most of the generated hydrocarbons are of biogenic origin. Sapropelic marine organic matter seems to be prevalent. Such type of organic matter is prone to produce more hydrocarbons at lower temperatures than humic terrigenous material (Tissot and Welte, 1978).

One of the outstanding characteristics of the Panama Basin is unusually high biological productivity which greatly determines sedimentological regimes in the basin. Thus, organic matter produced in large quantities under favorable conditions constitutes an important element in methanogenesis. The organic carbon which originates from organic matter is often used as an indicator of the sediment potential for bacterial hydrocarbon generation. It is widely accepted that a minimum 0.5% organic carbon is needed to sustain biogenic methanogenesis (Claypool and Kaplan, 1974). Figures 27 and 28 illustrate the total organic carbon (TOC) contents in vertical profiles of DSDP Sites 505, 84, 158, and 157. At Sites 158 and 157, particularly low values of TOC ranging from 0.2 to 0.5% were measured. Conversely, much higher TOC values (1 to over 2%) were revealed in the vertical profiles of Sites 505 and 84. It appears that a significantly higher degree of organic carbon preservation at the two latter sites is due to the higher rates of sedimentation (Muller and Suss, 1979). In all four profiles the variations of the TOC show good correlation with the sedimentation rates (Figure 17).

Biogenic methane was directly identified at DSDP Sites 505 and 504, using production index (P.I.) which measures the degree of thermal hydrocarbon generation in the sediment (Whelan and Hunt, 1983). The production index (P.I.) is defined as $P_1/(P_1 + P_2)$ where P_1 and P_2 represent two peaks from pyrogram obtained during pyrolysis of a sediment sample, low temperature peak (100 - 250°C) and high temperature (400 - 700°C) respectively (Espitalie et al., 1977). Geochemical results of the pore water analysis from the same sites reflect the processes of bacterial methanogenesis (Figures 29 and 30). The contents of SO_4^{2-}, Ca^{2+}, NH_3 and alkalinity show some characteristic features. The profiles of these chemical species are typical for the sites with rapidly deposited organic-rich hemipelagic sediments (Sayles and Manheim, 1975). Sulfate decrease and increase of the salinity are the direct result of the intensity of bacterial sulfate reduction using organic matter:

$$2CH_2O + SO_4^{2-} = H_2S + 2HCO_3^-$$

The increase of alkalinity causes calcite precipitation in the sediment and depletion of Ca^{2+} in the pore water.

In profiles of the borehole of Site 505, the zone of the most reducing conditions occurs at a subbottom oceanic depth of 100 m which was confirmed by the emission of gas bubbles and an intense H_2S odor detected upon recovering the core. The sediment pore water chemistry at Site 505 is largely affected by bacterial sulfate reduction and by diffusion processes between this zone and over- and underlying zones. The unaltered seawater geochemical characteristics at the bottom of the sedimentary sequence are caused by the seawater circulating through the basement.

Figure 26 shows vertical variations of the SO_4^{2-}, Ca^{2+}, salinity and alkalinity in the area of DSDP Sites 501/504. Decrease of sulfate with depth as well as shallow maxima in alkalinity and NH_3 almost certainly result from sulfate reducing bacterial activity. The vertical changes of alkalinity and Ca^{2+} show, however, that in Sites 501/504 pore water chemistry is not

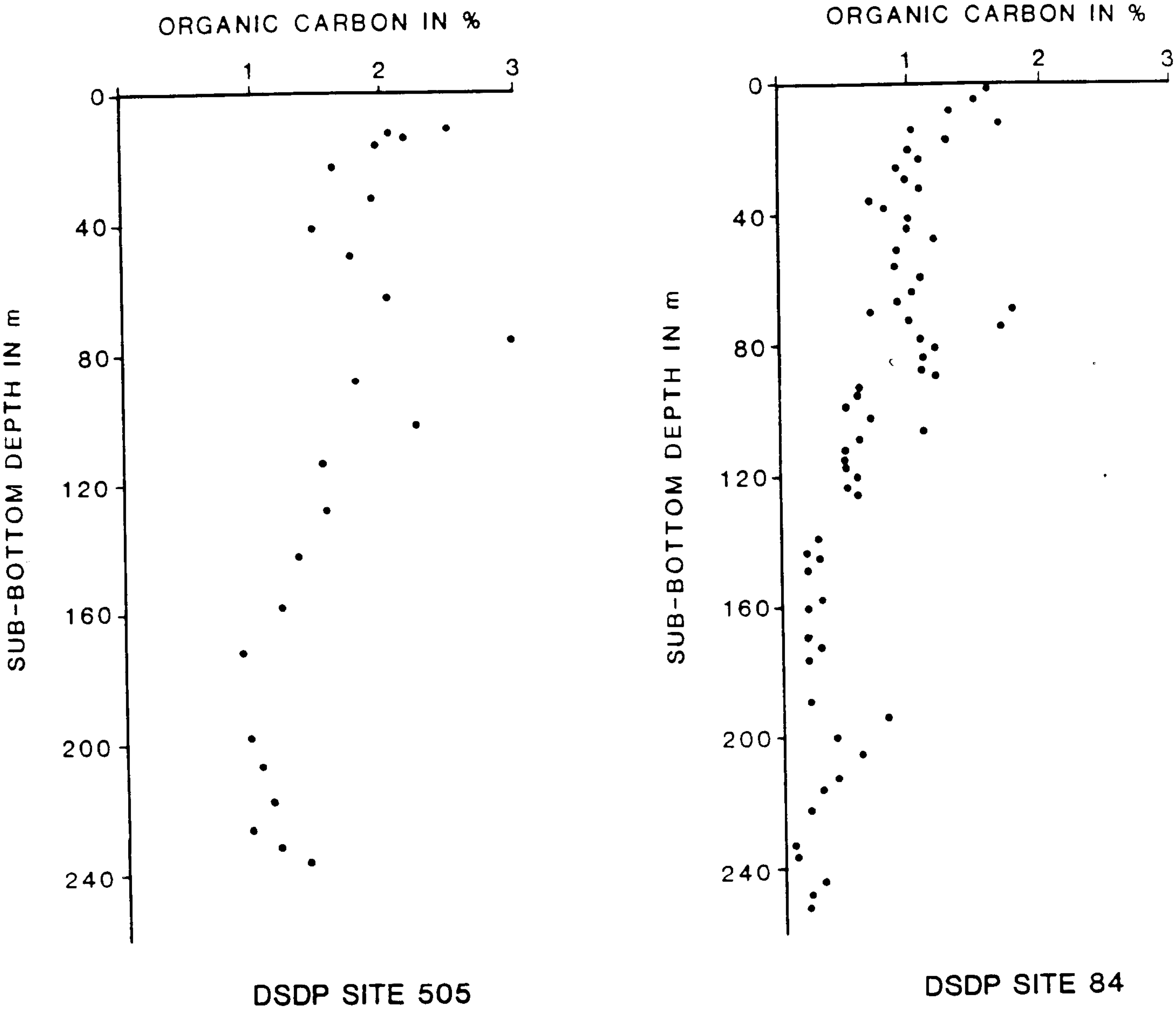
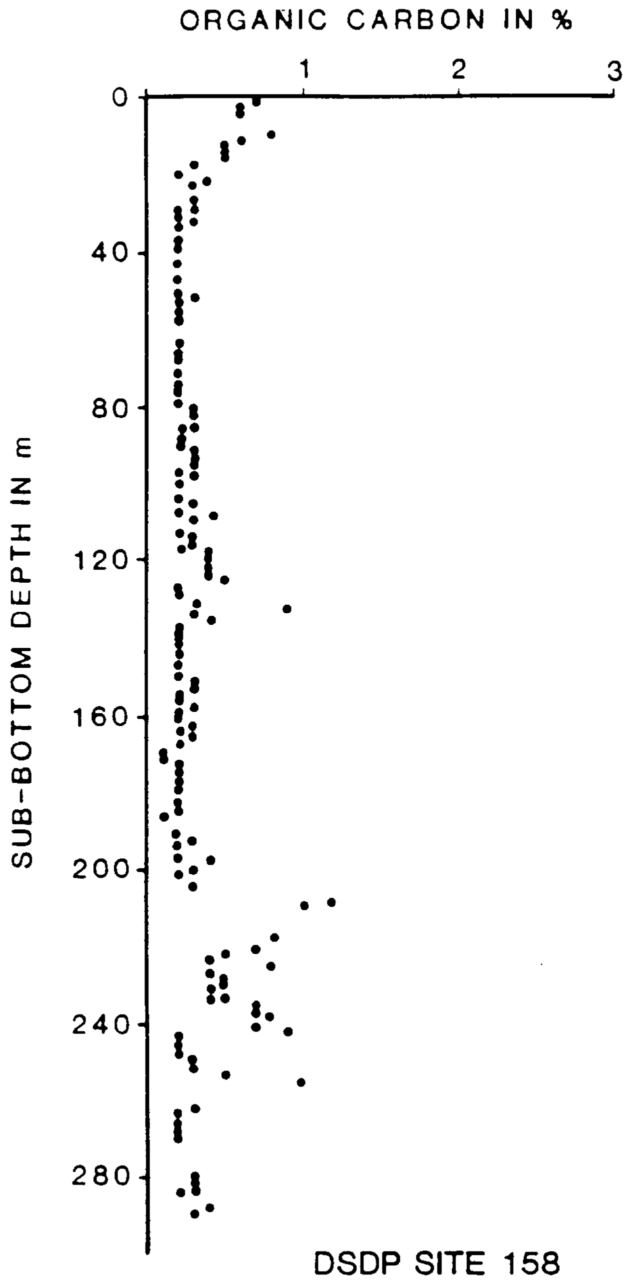


Figure 27. ORGANIC CARBON CONTENTS IN VERTICAL PROFILES OF DSDP SITES 505 (LEG 69) AND 84 (LEG 9)

After Whelan and Hunt, 1982



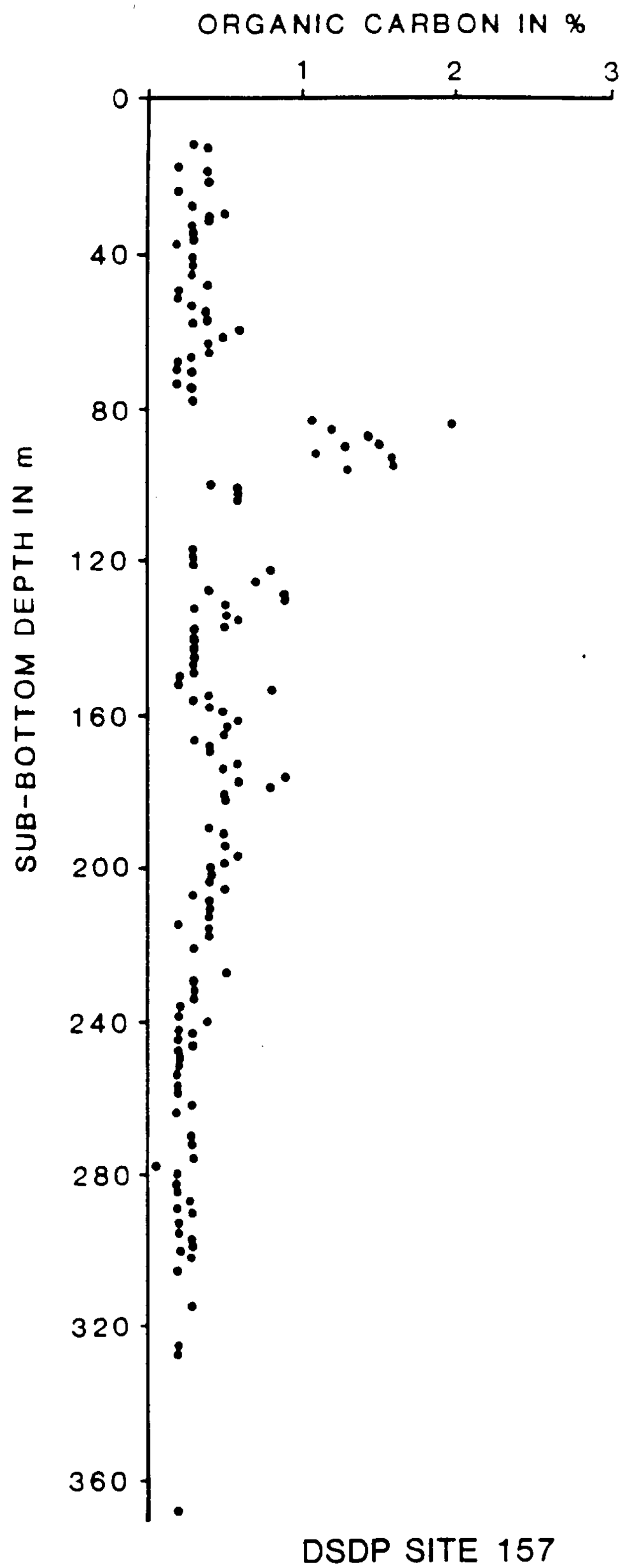


Figure 28. ORGANIC CARBON CONTENTS IN VERTICAL PROFILES OF THE DSDP SITES 158 AND 157 (LEG 16)

After Bode, 1973

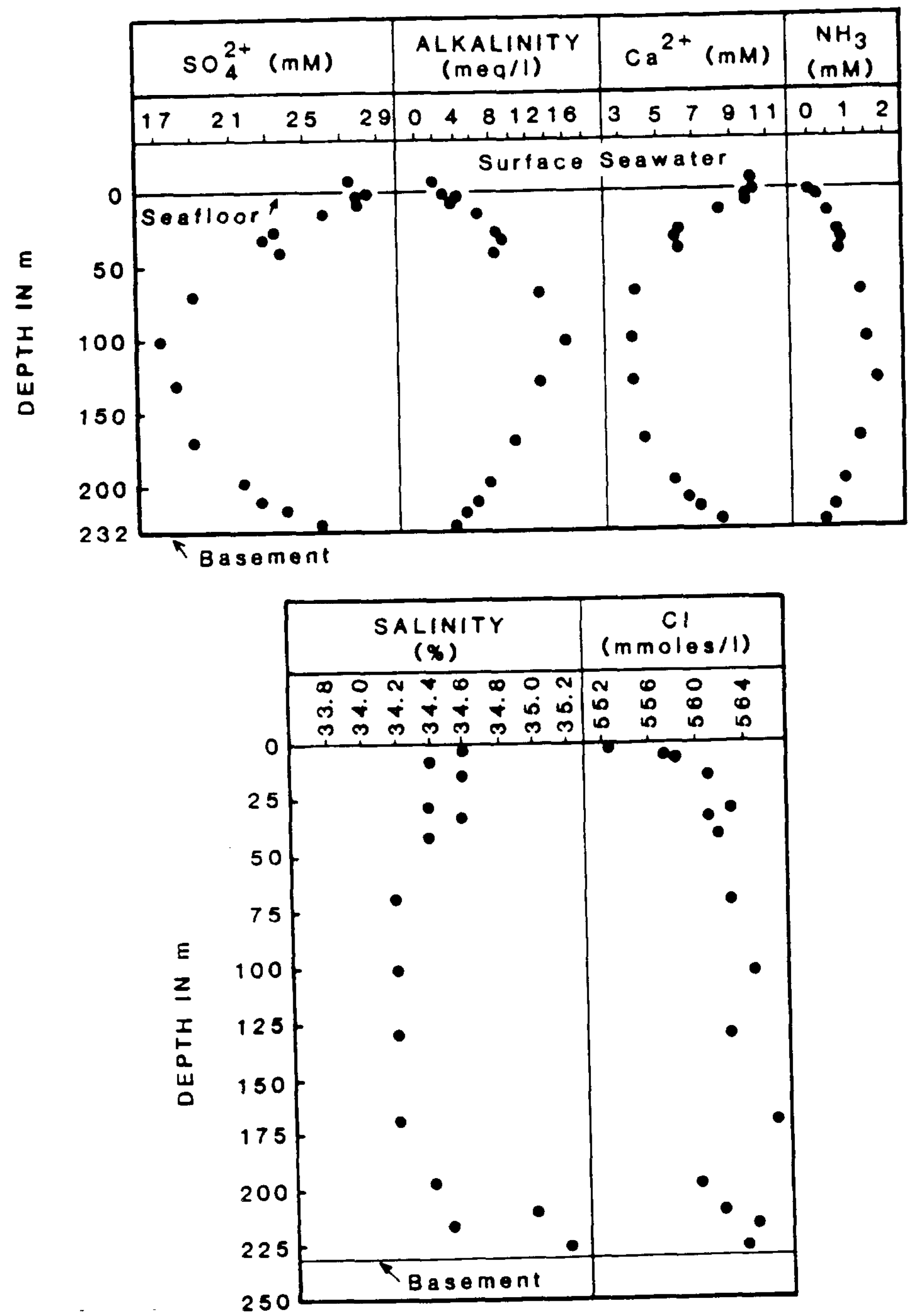


Figure 29. COMPOSITION OF SEDIMENT PORE WATERS – DSDP SITE 505

Modified after Mottl et al., 1982

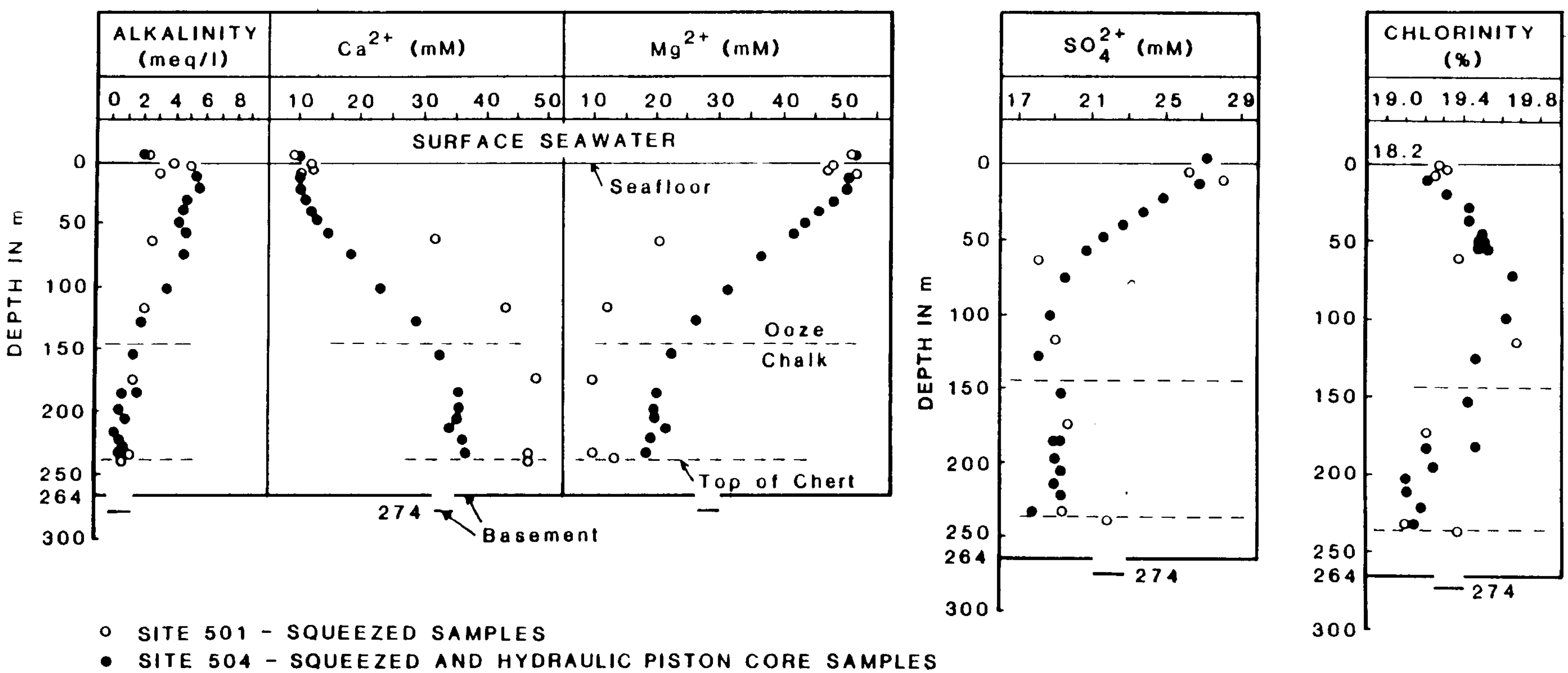


Figure 30. COMPOSITION OF SEDIMENT PORE WATERS – DSDP SITES 501/504

Modified after Mottl et al., 1982

dominated by bacterial activity. Enrichment of the pore water in Ca^{2+} accompanied by Mg^{2+} has been attributed to the alterations of the basement basalts (McDuff, 1981).

The geochemical data from the sediment pore water of Sites 505, 501/504 are the sole available geochemical information and represent only a very fragmentary picture in the Panama Basin. These data demonstrate, however, the presence of active reducing zones in the Panama Basin sediments where biogenic hydrocarbons originate.

The greatest efficiency of biogenic methane production occurs in areas of high biological production where relatively high rates of sedimentation (>50 m/m.y.) take place. Anoxic conditions can be maintained even at shallow depths when the rates of the organic matter input exceed the amount of the supplied oxygen. It appears that optimum combination of the environments favorable for the hydrocarbon generation occur at lower parts of the continental slopes and upper continental rise of Panama, Colombia and Ecuador offshore. Detailed evaluation of the hydrocarbon generation in the Panama Basin requires more data which are presently not available.

Seismic Evidence for Gas Hydrates

Seismic data are frequently used for identification of the presence of gas hydrates in sediments. The anomalous seismic reflectors referred to as the bottom simulating reflectors (BSRs) often seen on the seismic records from continental slopes and rises are interpreted by many authors as the base of the gas hydrate-bearing zone (Stoll et al., 1971; Ewing and Hollister, 1972; Dillon et al., 1980; Kvenvolden and McMenamin, 1980; and others). As a phenomenon dependent on distribution of isogeotherms, BSRs intersect reflections from sedimentary strata and mimic the topography of the sea floor.

The Panama Basin BSRs were first identified by Shipley et al. (1979) on multichannel common depth point (CDP) seismic profiles obtained by the University of Texas, Marine Science Institute in July, 1977. Figures 32 through 36 show several BSRs identified during this study. Our review of available seismic sections from the Ecuador offshore revealed the presence of some BSRs east of the Ecuador Trench. All BSRs will be described in the following sections of this report.

During the past several years numerous attempts were made toward better understanding the nature of the anomalous seismic responses from sediments with gas hydrate-bearing zones and from underlying free gas zones. The investigations of the temperature-pressure conditions in the localities containing BSRs invariably show their compliance with gas hydrate stability area (Tucholke, 1977). Further evidence on the relationship between BSRs and gas hydrates came with results from the investigations of seismic velocities in sediments where the BSRs were previously identified. Lancelot and Ewing (1972) determined an apparent acoustic velocity of 2 km/s through sediments overlying the BSR reflectors. The determinations by the latter authors were confirmed by the independent sonobuoy measurements (Bryan, 1974). Bryan found that values of the acoustic velocities in the gas hydrate zones were unusually high as for the hemipelagic type of sediments.

Other efforts were made to find criteria enabling us to differentiate gas hydrate related seismic reflections from other unusual seismic responses.

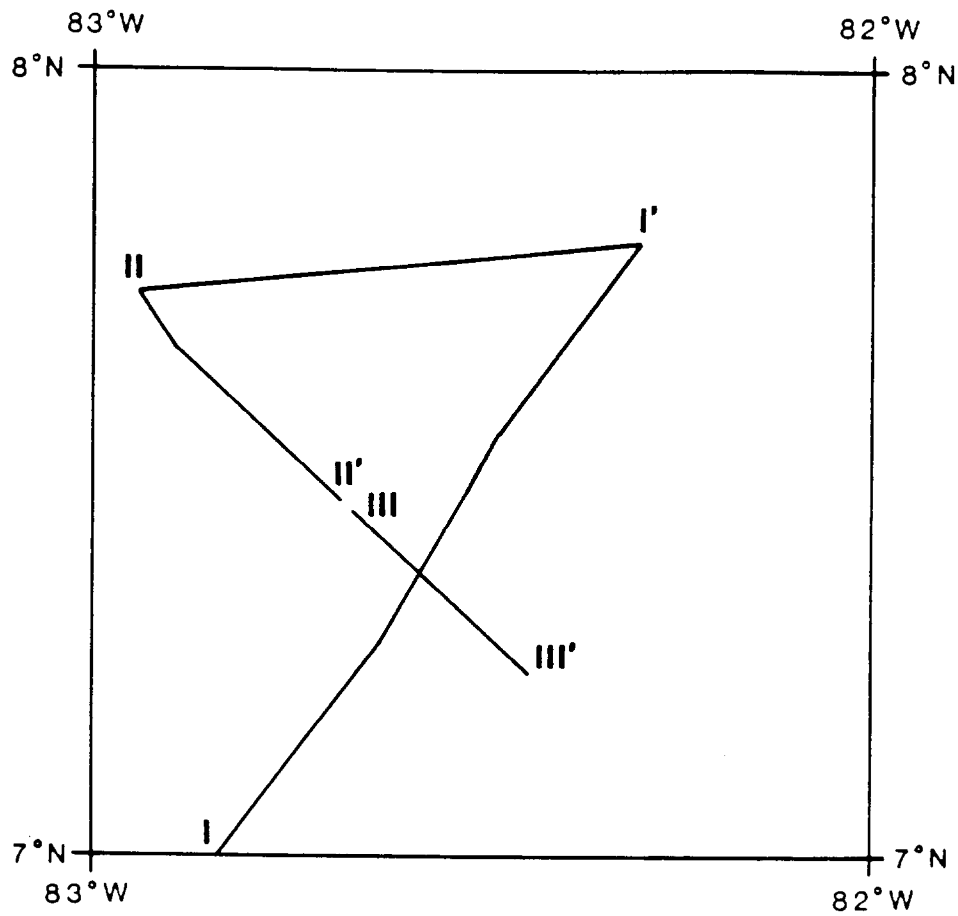
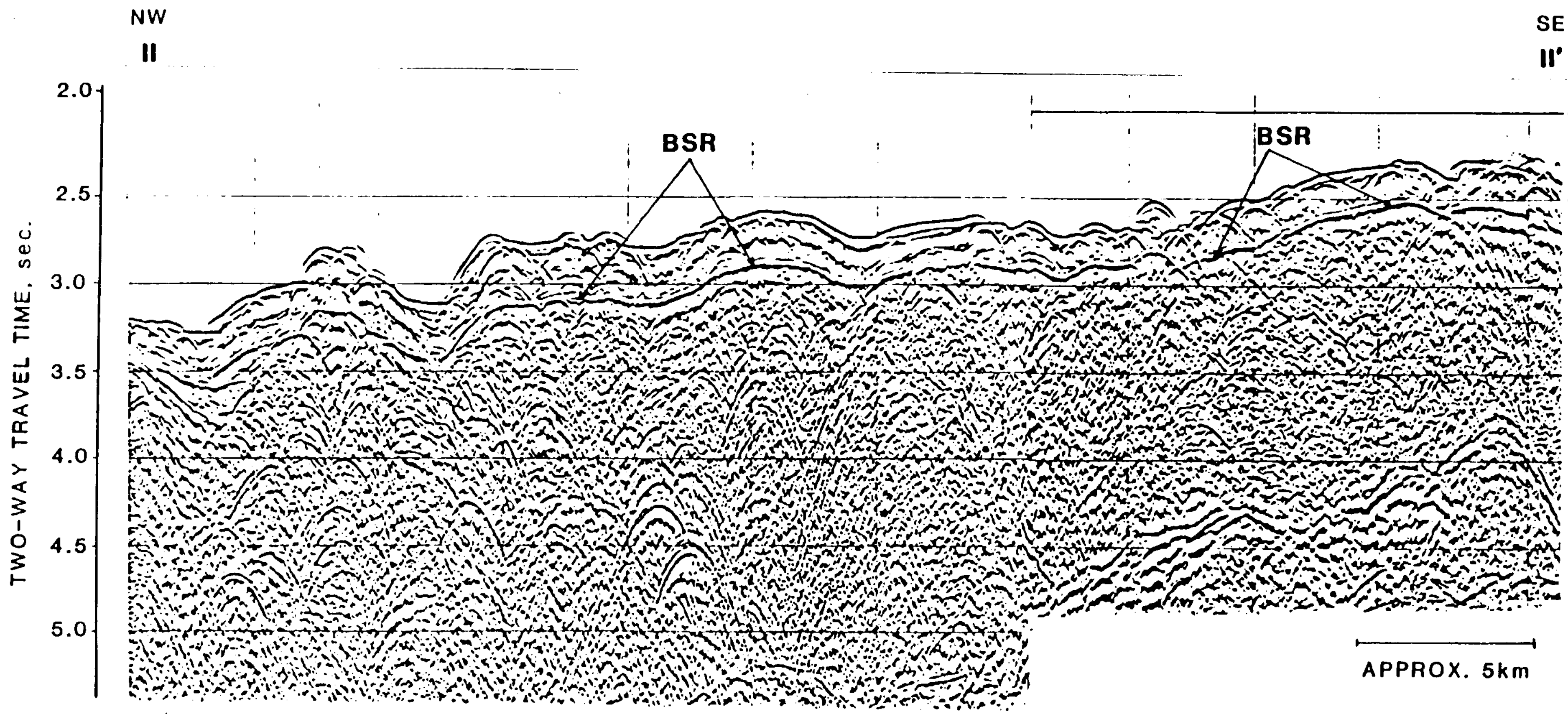


Figure 31. MAP OF TRACK-LINES OF SEISMIC PROFILES PRESENTED ON FIGURES 32-35

FIGURE 32, Seismic Line I'-I, Offshore Panama, is located in the pocket at the end of the report.

FIGURE 33, Seismic Profile I'-II, Offshore Panama, is located in the pocket at the end of the report.



FOR DETAILED TRACK-LINE SEE FIGURE 31

Figure 34. SEISMIC PROFILE II-II', OFFSHORE PANAMA

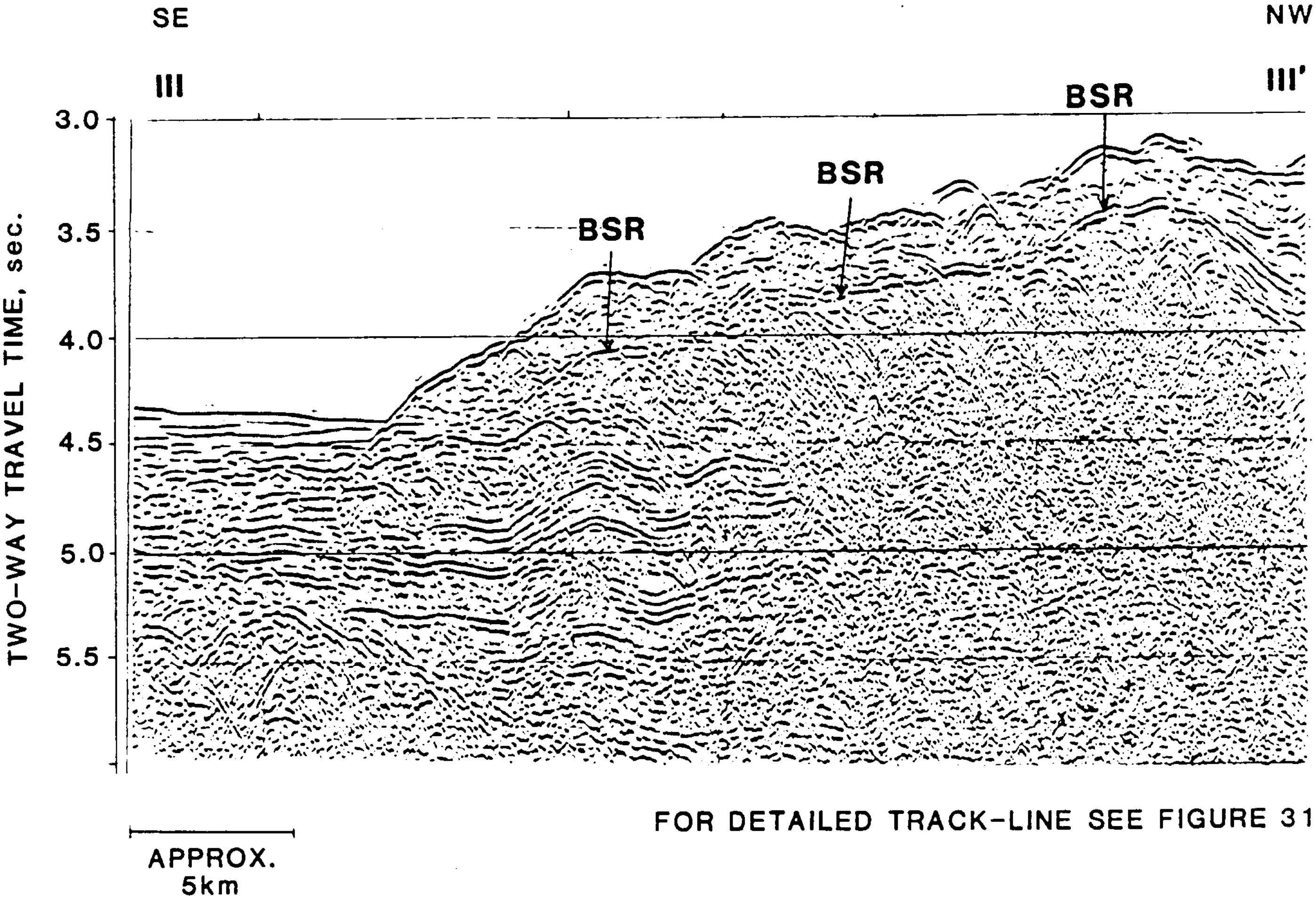


Figure 35. SEISMIC PROFILE – III–III', OFFSHORE PANAMA

FIGURE 36, Seismic Profile IV-IV', is located in the pocket at the end of the report.

Besides the compliance with temperature-pressure stability conditions of gas hydrates, Bryan (1974) and Shipley et al. (1979) suggested considering three features of BSRs:

1. reflection polarity reversal,
2. large reflection coefficient, and
3. increased subbottom depth of the BSR with increasing water depth.

The concentration of free gas below gas hydrate zone should alter the formation density and acoustic velocity. Thus the boundary between gas hydrate zone and free gas zone should be reflected by the seismic polarity reversal and negative reflection coefficient. The seismic reflection coefficient (R) has been suggested as a measure of the acoustic velocity and formation density changes.

$$R = (\rho_2 V_2 - \rho_1 V_1)/(\rho_1 V_1 + \rho_2 V_2)$$

where,

R = seismic reflection coefficient

ρ_1, ρ_2 = formation density in gas hydrate zone and in free gas zone,

V_1, V_2 = acoustic velocities in gas hydrate zone and in free gas zone.

The relationship between water depth and subbottom depth of the BSR occurrence is perceived as an important indicator of the possible gas hydrate zone. If the BSRs indeed represent the base of the gas hydrate zone their depth of occurrence should change with depth of the sea floor according to altered pressure conditions. This relationship is not always found within areas comprising the anomalous seismic reflections, which implies that BSRs may represent a boundary other than a hydrate base, for example a phenomenon caused by diagenesis (Hein et al., 1979). The analysis of BSRs in various parts of the continental margin of North and Central America by Shipley et al. (1979) showed that at ocean depths below 2,000 meters the changes of gas hydrate base due to the variations in water column depth are significantly smaller than in shallower areas.

The Panama Basin represents a region with a significant shortage of seismic recordings suitable for BSR identification. Analysis of the available data made it possible to identify the BSRs in four seismic profiles of the Panama offshore (Figures 31 to 35) and in one seismic line from the Ecuador offshore between the easternmost tip of the Carnegie Ridge and South America (Figure 36). In the BSR classification proposed by Tucholke et al. (1977) most of the identified BSRs represent Class 1 and 2 reflectors, i.e. feature strong returns and are laterally continuous or discontinuous only in some sections.

Profile I-I' (Figure 32). Bottom simulating reflectors have been identified in the middle section of the continental slope. Generally, these reflectors mimic the topography of the sea floor. The acoustic depths of the BSRs in this profile vary from 0.3 to 0.45 sec. Water depth along the seismic line ranges from 250 m to 3,400 m.

Profile I'-II (Figure 33). In this seismic profile the BSRs are noticeable in the relatively flat section of the ocean floor below 1,800 m of water depth. The acoustic depths of the BSR reflectors are similar to those present in the profile I-I' and range from 0.3 to 0.42 sec. Variations of the presumed gas hydrate zone display favorable conditions for free gas entrapment under the gas hydrate zone. Contrary to profile I-I', the relatively steep slope precludes the occurrence of gas hydrates which is most likely due to the combined role of two factors: sediment instability and less favorable conditions for methanogenesis compared with flatter areas.

Profiles II-II' and III-III' (Figures 34 and 35). The water depth along these two seismic profiles ranges from 1,200 to 2,600 m. BSRs of class 1 occur in seismic profile II-II' representing shallower area, while in the profile III-III' the discontinuity of the anomalous reflectors can be observed. Acoustic depths of the BSR reflectors in both profiles varies from 0.23 to 0.39 sec. Also a slight decrease in the return signal amplitude is noticeable above the hydrate zone.

Profile IV-IV' (Figure 36) represents the sole seismic section from the eastern Panama Basin. Continuous BSRs can be easily spotted along the track where ocean water depth ranges from approximately 750 to 2,600 m. The acoustic depth of these BSRs varies from 0.25 sec in the upper middle continental slope to 0.42 sec in proximity of the trench zone. The BSRs tends to fade away in the area close to the trench. The subbottom depths of the BSR show good correlation with the variations of the ocean depth. As with the previously described profiles, the amplitudes of return signals above the BSRs are diminished.

Although there is no direct confirmation of the presence of gas hydrates by drill holes in those areas of the Panama Basin where BSRs occur, there are good indications which increase the probability that most identified BSRs are indeed related to gas hydrate-bearing zones. A cursory check of the temperature-pressure conditions in the areas of BSR occurrence invariably show the coincidence with the area of the gas hydrate stability. Strong reflection polarity reversal for two single seismic records from the areas of south Panama offshore were shown by Shipley et al. (1979; Figure 37). The seismic signal reflection coefficients from the same area display comparable values with those from the Blake Outer Ridge where occurrence of gas hydrates is highly probable (Table 7; Shipley et al., 1979).

TABLE 7.

ESTIMATED VERTICAL SEISMIC REFLECTION COEFFICIENTS, After Shipley et al., 1979.

Area	Water bottom	Reflection Gas hydrate	Coefficients % change	Number of shots
Blake Outer Ridge	0.21 ± 0.04	-0.12 ± 0.04	-21 ± 8	13
Eastern Pacific Ocean	0.18 ± 0.02	-0.05 ± 0.03	-10 ± 6	10

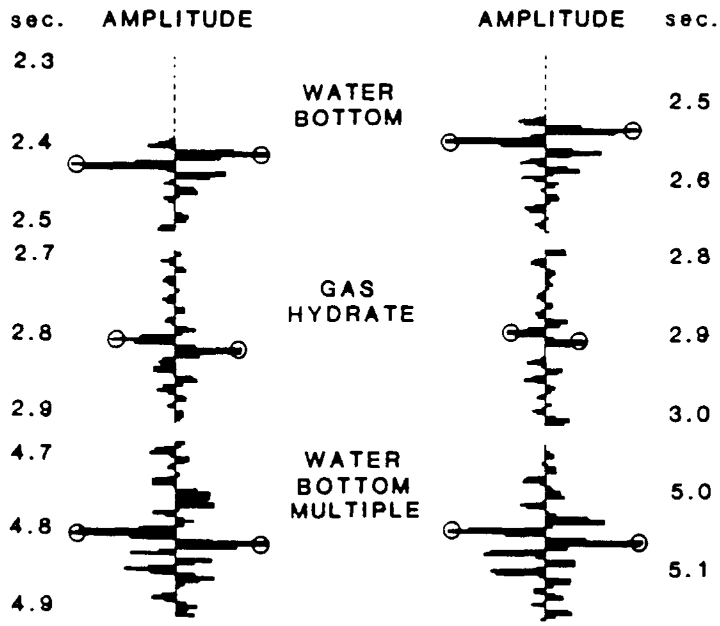


Figure 37. **REVERSAL OF REFLECTION POLARITY ASSOCIATED WITH GAS HYDRATES EXEMPLIFIED ON TWO SINGLE-TRACE SEISMIC REFLECTION RECORDS FROM THE PANAMA OFFSHORE AREA**

After Shipley et al., 1979

A strong correlation between water depth and subbottom depths of the BSRs in various offshore regions including the Panama Basin has been shown by Shipley et al. (1979; Figure 38). Such correlation seems to indicate the common origin of the BSRs formed under different geothermal conditions (Figure 38). The curve for the Panama Basin indicates that BSRs in this region are found at unusually shallow subbottom depths which is probably due to relatively high geothermal gradient. There are two zones presented in the seismic profiles in Figures 32 - 35, where the identified BSRs do not quite conform with the above mentioned relationship. One of these zones is noticeable in the profile I'-I (Figure 32). The actual subbottom depth of the BSR increases in the up-slope direction. Despite the fact that the zone above this presumed BSR reflector may conform to requirements for gas hydrate stability, diagenetic processes as well as local variations in geothermal regime could be responsible for this type of BSR occurrence (Claypool and Kaplan, 1974). Another similarly abnormal BSR has been spotted in seismic profile I'-II (Figure 33) in the area of ocean floor adjacent to the lower continental slope.

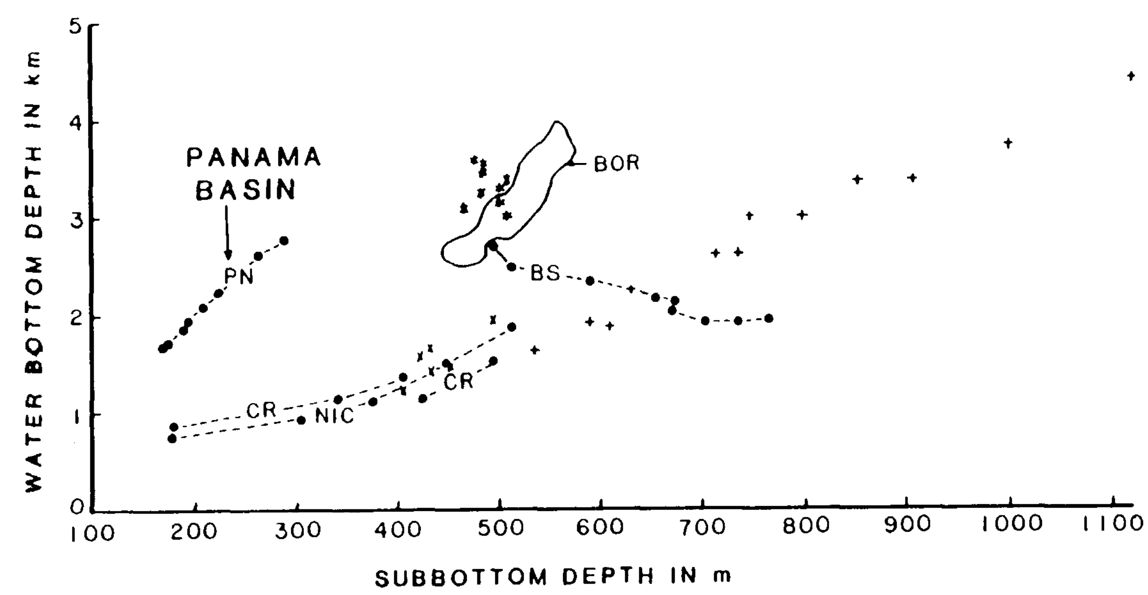
Assessment of Gas Resources in Gas Hydrates

The Panama Basin represents the region where the potential occurrence of gas hydrates has not been verified by drilling. Severe data gaps still exist in lithology and geochemistry related to the processes of methanogenesis. The data gaps are particularly big on the continental margins of Panama, Colombia and Ecuador. Therefore, in the gas potential assessment only very preliminary figures could be produced.

Most of the Panama Basin bathymetric environments fulfill the temperature and pressure requirements for gas hydrate stability. The processes of organic matter preservation and further methanogenesis seem to be major factors controlling gas hydrate distribution. Although the coverage of the Panama Basin with the multichannel seismic profiles is not adequate, the existing records fully support what has been stated above. The continental margins are major locations of potential gas hydrate zones. The thickness of the gas hydrate-bearing zone(s) based on the BSRs identified in the seismic profiles may vary from 200 to 336 m. The maximum ocean depth at the locations with newly identified BSRs is approximately 2,600 m.

It is estimated that the area of continental margins of Panama and Colombia favorable for gas hydrate occurrence within the Panama Basin extends over $6.4 \times 10^{10}\,m^2$. Assuming 40% sediment porosity and 12% pore space filling, 5% of the sediment volume will be filled with gas hydrates. Furthermore, using the gas volume conversion factor from gas hydrates 200:1 estimated by Kuuskraa et al. (1983) for standard conditions, the gas resource in the hydrate state (assuming 30% areal extent for the hydrate zone) should amount to:

$$\begin{gathered}1 \text{ m thickness} \times 6.4 \times 10^{10}\ m^2 \text{ area} \times 5\% \text{ hydrate} \times \\ 30\% \text{ areal extent} \times 200 \text{ volume conversion factor} = \\ 1.92 \times 10^{11}\ m^3\ (6.8\ \text{TCF})\end{gathered}$$



BOR BLAKE OUTER RIDGE (Tucholke et al.)
* BLAKE OUTER RIDGE
x WESTERN GULF OF MEXICO
PN EASTERN PACIFIC, PANAMA
CR EASTERN PACIFIC, COSTA RICA
NIC EASTERN PACIFIC, NICARAGUA
\+ EASTERN PACIFIC, MEXICO
BS BERING SEA

Figure 38. **GRAPH ILLUSTRATING SUBBOTTOM DEPTH OF IDENTIFIED BOTTOM SIMULATING REFLECTORS (BSRs) AND WATER COLUMN DEPTH**

After Shipley et al., 1979

The gas volume contained in a hydrate layer of various mean thicknesses will be:

1 m = 1.92×10^{11} m^3 (6.8 TCF)
100 m = 1.92×10^{13} m^3 (680 TCF)
200 m = 3.84×10^{13} m^3 (1,360 TCF)
300 m = 5.76×10^{13} m^3 (2,040 TCF)

Data Gaps

The evaluation of gas hydrate formation and stability in the Panama Basin is restricted by the severely limited amount of relevant data. Particularly, a lack of information exists in the areas of the continental margins. Before more detailed assessment of gas hydrates is possible the following data must be available:

1. More advanced, properly spaced multichannel seismic survey profiles,

2. Drilling data including:
   a. detailed lithology,
   b. petrographic analysis,
   c. geochemistry (organic and inorganic), including isotopic data of in-situ samples of the sediment organic matter and pore water,

3. Detailed geothermal data.

Conclusions

The Panama Basin represents a huge region of approximately 1,200,000 km^2. Some principal aspects of geological evolution of this complex basin are still in the process of scientific debate. Among the most important issues for the gas hydrate potential assessment are the following:
- origin of major ridges
- origin and evolution of the Panama Isthmus
- nature of the Pacific Ocean continental margin of Panama
- sedimentary processes in the continental margins within the Panama Basin

The potential for gas hydrates in the western part of the Panama Basin (west of the 85°W Fracture Zone) is practically precluded by thin sedimentary cover ranging from 0 to 35 m. The presence of some favorable factors for gas hydrate formation in the eastern part of the Panama Basin (east of the 85°W Fracture Zone) were the main reason for undertaking this study despite a great paucity in the existing data inventory. The review of the geological history of the Panama Basin within boundaries of currently proposed hypotheses and analysis of major factors required for gas hydrate formation enabled formulation of the following conclusions:

1. Thickness of sediments in the Panama Basin ranges from 0 to over 2,000 m (van Andel et al., 1971; Lowrie, 1978). In most parts of the basin the thickness of sedimentary sequences does not exceed 600 m. Only in local depressions, and in the northern and eastern marginal parts of the basin, are much thicker sediments present. Three types of sedimentary cover have been observed in the Panama Basin:

   a. continuous sedimentary cover rests on the oceanic floor (i.e. in ridges and environs; the cover is occasionally disrupted by an uplifted basement),

   b. discontinuous sedimentary cover; occurs mainly at the oceanic floor in rugged areas of the central part of the Panama Basin,

   c. thick sedimentary cover; occurs in areas of continental slopes and upper rises.

2. Lithologically the sedimentary sequences in the DSDP sites display a significant degree of similarity. The prevailing amount of sediments is of biogenic origin. More terrigenous material is present in the continental shelf and slopes.

3. While the general heat flow in the Panama Basin is high (above 2 HFU), the geothermal regimes within the basin are diverse. At least three major geothermal regimes can be distinguished:

   a. a geothermal regime within the continuous sedimentary cover where no major outcrops of basement in the oceanic floor occur, e.g. in the vicinity of DSDP Sites 501/504. The maximum temperature to which sediment is exposed at the contact with the basement is approximately 59°C while the average temperature at the oceanic floor is only 2.5°C and the thickness of the sedimentary sequence is 234 m,

   b. a geothermal regime within rugged areas of the basin with numerous basement outcrops and faults where offsets exceed 100 m, e.g. in the vicinity of DSDP Site 505. The temperature of 9°C at the contact of the sedimentary sequence (242 m thick) and basement is probably caused by the convective type of heat exchange with the oceanic water.

   c. a geothermal regime of the northern end of the eastern basin margins where the thickness of sedimentary sequences exceeds 2,000 m and geothermal gradients range from 0.04 to 0.05°C/m.

4. The entire Panama Basin is characterized by unusually high biological productivity which constitutes a favorable condition in the supply of organic matter to the sediment.

5. The process of biogenic methanogenesis is hindered in large areas by the oxidation of organic matter.

6. The needed balance for maintenance of reducing conditions is probably reached only in the areas where the highest biological production is combined with higher rates of sedimentation (exceeding 45-50 m/m.y.). Such conditions are likely to exist in continental slopes and in the vicinity of elevated areas (ridges).

7. Due to the relatively low temperatures to which sediments are exposed, most of the preserved organic matter is too immature for thermal hydrocarbon generation. Biogenic methane generation seems to be prevalent in supplying hydrocarbon gas for the gas hydrate.

8. The identified BSRs represent only a fraction of possibly existing anomalous reflectors related to gas hydrates in the continental margins of Panama, Colombia and Ecuador.

9. The analysis of identified BSRs suggests their strong relationship with the base of the gas hydrate zone.

10. Diagenetic processes, particularly in sediments of the continental margins, cannot be evaluated at the present time due to a lack of core information.

11. Gathered and analyzed data indicates that the most favorable conditions for gas hydrates occur in areas of relatively flat continental slopes and upper rises where the oceanic water depth does not exceed 2,400 m. The latter constraint is probably caused by oxidation of organic matter.

12. Seismic profiles with presumed gas hydrate zones show considerable variations in the base of the zone. The gas hydrate zone can thus create closures in which the free hydrocarbon gas is likely to be trapped.

13. Estimated resources of hydrocarbon gas accumulated in the hypothetical hydrate zone of the continental margin within the Panama Basin show a value of 6.8 TCF per 1 m of thickness of sediment saturated with the gas hydrate.

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